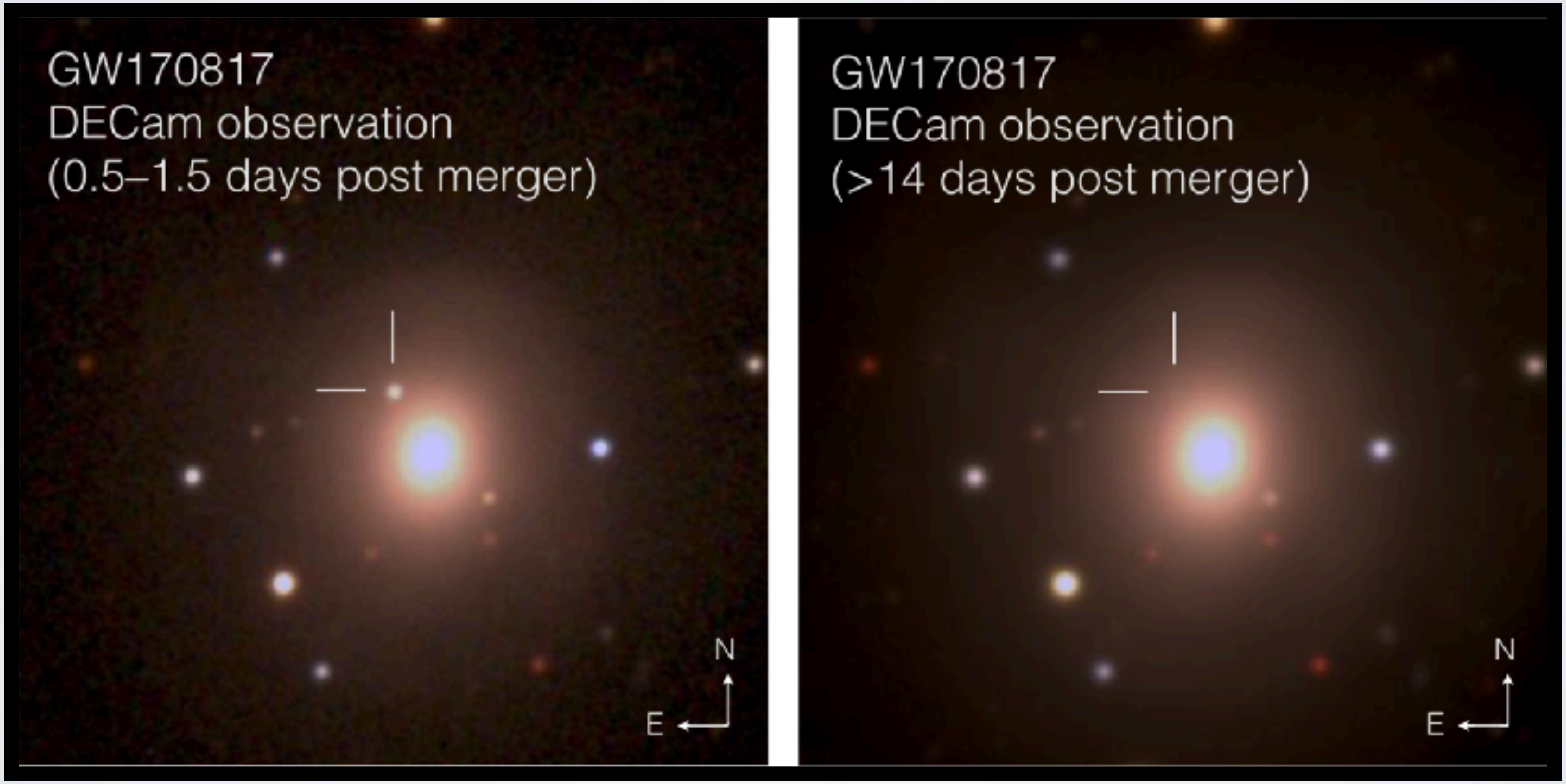
OBSERVATION OF A GRAVITATIONAL WAVE EMITTING NEUTRON STAR MERGER WITH THE DARK ENERGY CAMERA

Marcelle Soares-Santos ◆ Brandeis University ◆ DES Collaboration



Fermilab Wine & Cheese Seminar ◆ October 20, 2017

THE DESGW TEAM

M. Soares-Santos, D. E. Holz, J. Annis, R. Chornock, K. Herner, E. Berger, D. Brout, H. Chen, R. Kessler, M. Sako, S. Allam, D. L. Tucker, R. E. Butler, A. Palmese, Z. Doctor, H.T. Diehl, J. Frieman, B. Yanny, H. Lin, D. Scolnic, P. Cowperthwaite, E. Neilsen, J. Marriner, N. Kuropatkin, W. G. Hartley, F. Paz-Chinchón, K. D. Alexander, E. Balbinot, P. Blanchard, D. A. Brown, J. L. Carlin, C. Conselice, E. R. Cook, A. Drlica-Wagner, M. R. Drout, F. Durret, T. Eftekhari, B. Farr, D. A. Finley, R. J. Foley, W. Fong, C. L. Fryer, J. García-Bellido, M. S .S. Gill, R. A. Gruendl, C. Hanna, D. Kasen, T. S. Li, P. A. A. Lopes, A. C. C. Lourenço, R. Margutti, J. L. Marshall, T. Matheson, G. E. Medina, B. D. Metzger, R. R. Muñoz, J. Muir, M. Nicholl, E. Quataert, A. Rest, M. Sauseda, D. J. Schlegel, L. F. Secco, F. Sobreira, A. Stebbins, V. A. Villar, K. Vivas, A. R. Walker, W. Wester, P. K. G. Williams, A. Zenteno, Y. Zhang,

Brandeis, UChicago, Fermilab, Ohio U, Harvard, UPenn, Indiana U, UCL, U Zurich, NCSA, U Surrey, Syracuse, LSST, Nottingham, TAMU, UCSC, IAP, UCSC, Northwestern, LANL, IFT/Madrid, SLAC, Penn State, Berkeley, URRJ/OV, U Chile, Michigan, STSCI/JHU, Unicamp, NOAO/CTIO

GW+EM OPPORTUNITIES

Astrophysics

- **First observations of NS-NS**, NS-BH mergers
- **Evolution of binary systems and their environment**
- **Origin of r-process elements in the Universe**
- **Neutron Star equation of state**
- Potential for discovery of new astrophysical phenomena

Cosmology

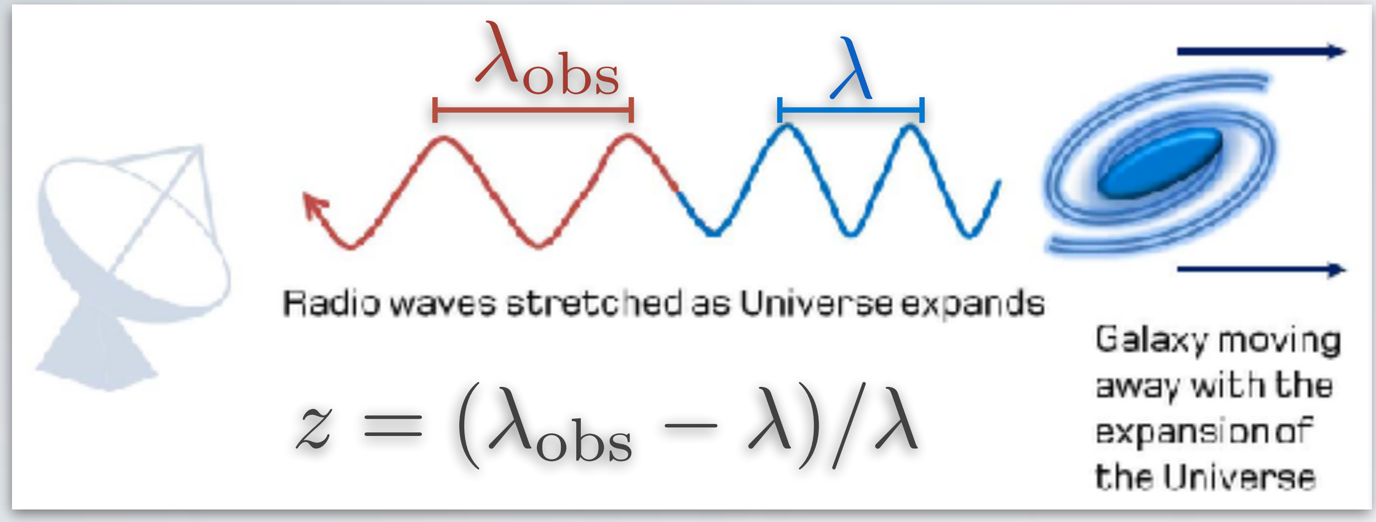
- **Standard sirens** (the GW-equivalent of standard candles)*****

Physics of space-time

- Time of flight experiments (including neutrinos)
- Tests of General Relativity

***Speaker's favorite!**

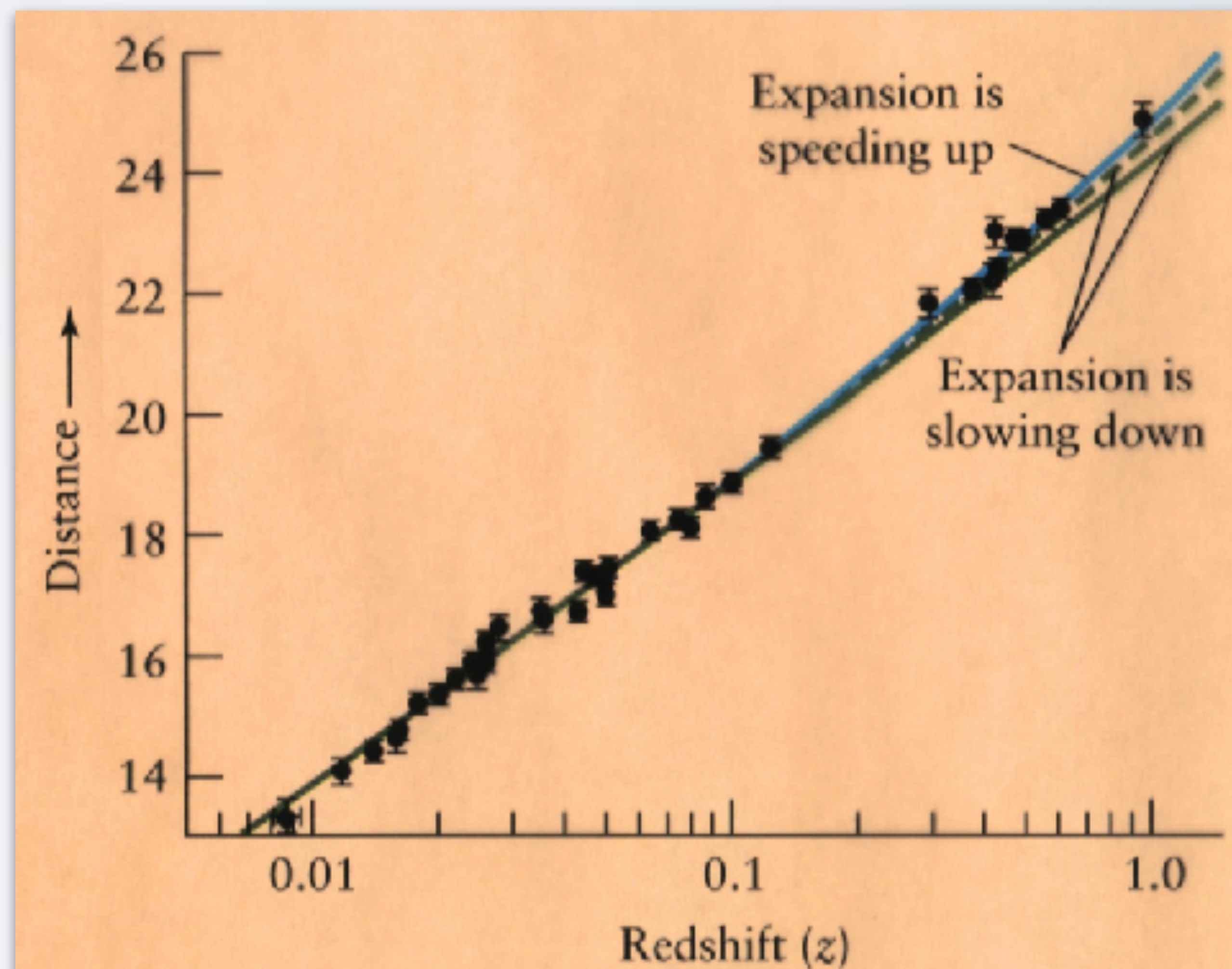
DISTANCE–REDSHIFT RELATION



Redshift (**z**) is an observable effect of the expansion of the Universe.

Faraway sources are more affected then nearby ones.

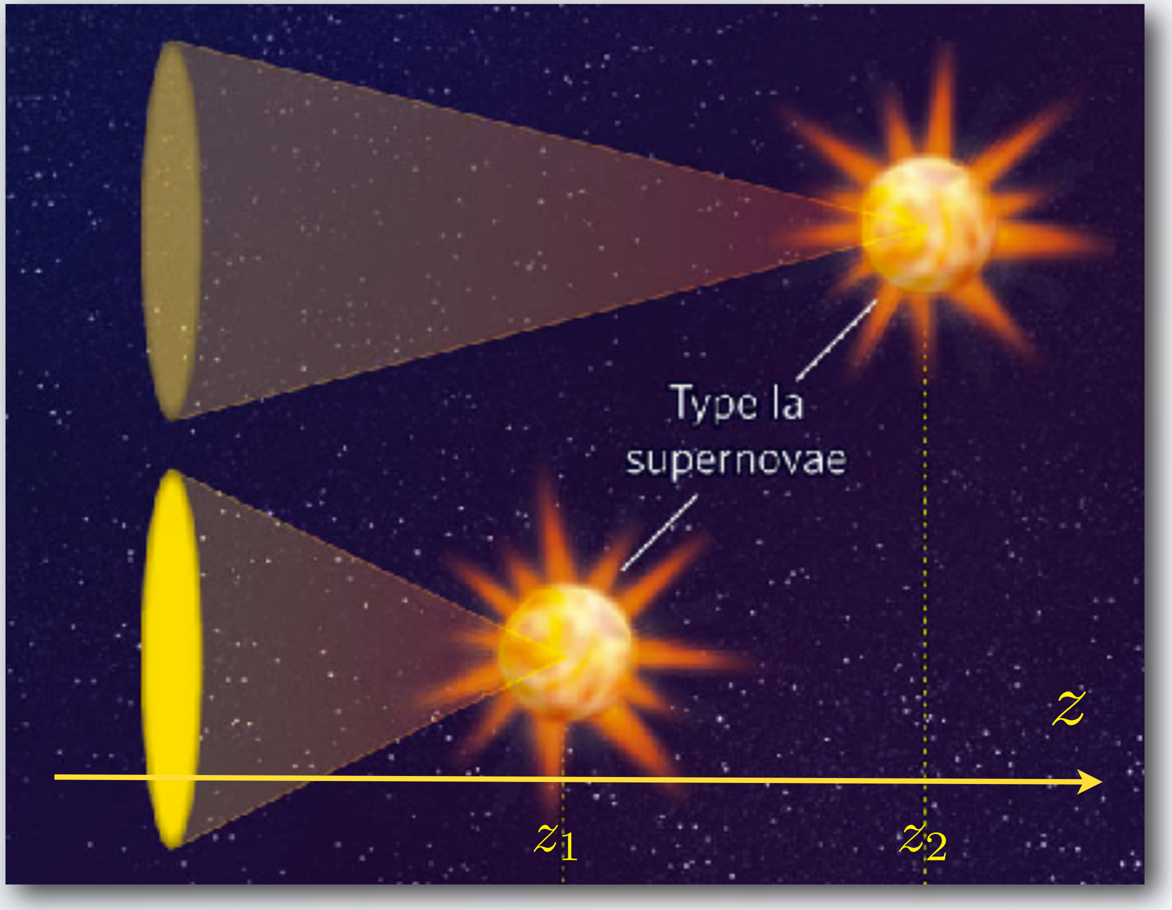
We can measure the rate of expansion using the **distance–redshift** relation!



ASTROPHYSICAL OBSERVABLES TO MEASURE DISTANCES

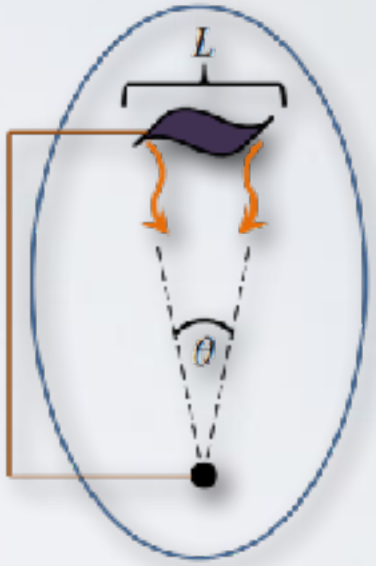
standard candle

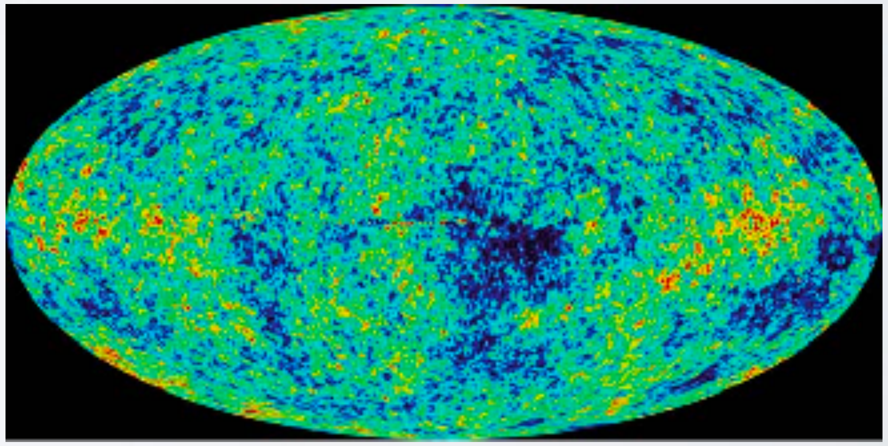
Type Ia Supernovae (SNe)



standard ruler

Cosmic Microwave Background (CMB)

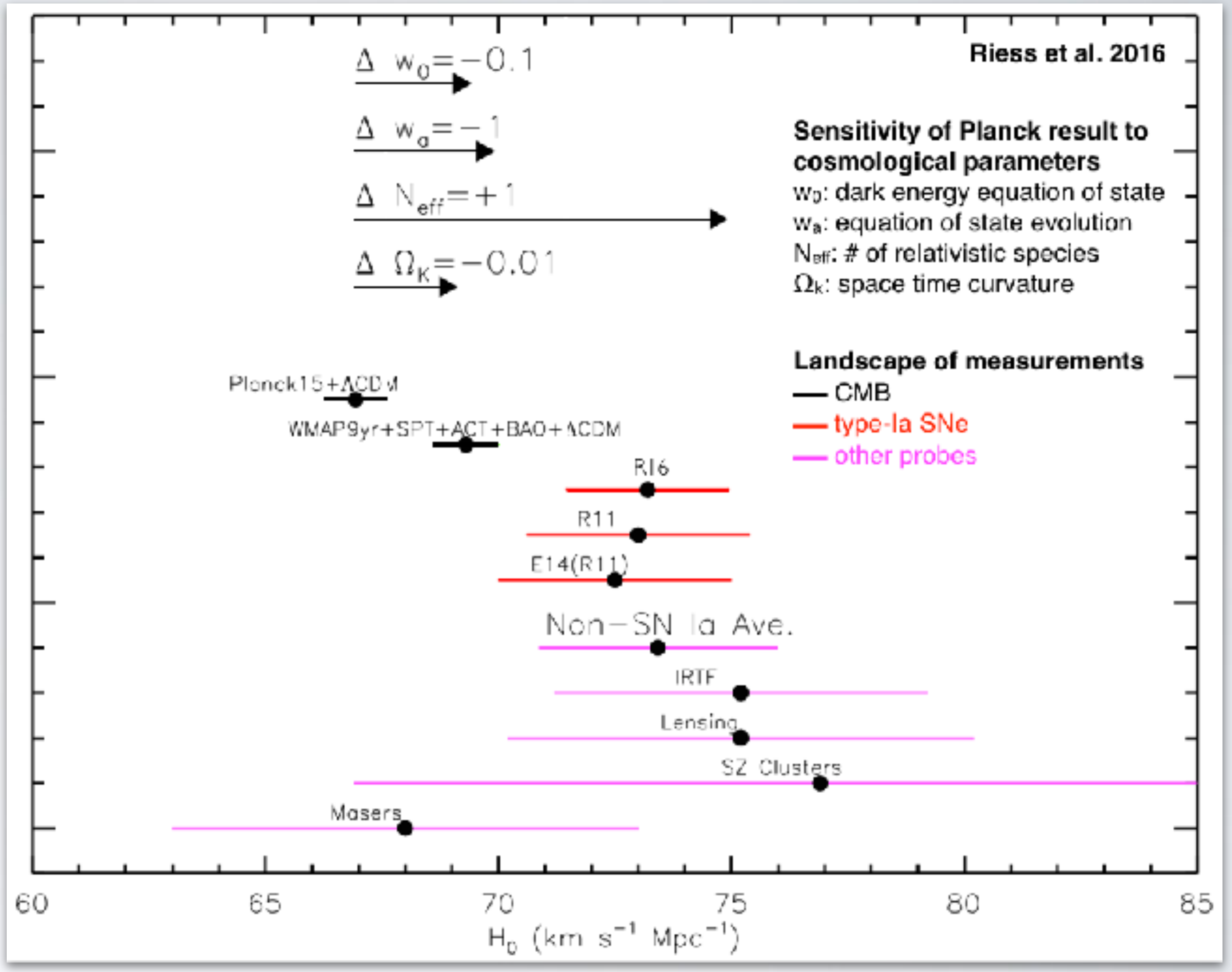




COSMOLOGY MOTIVATION

Growing discrepancy between SNe and CMB-based measurements of the current rate of expansion: **systematic effects, or new physics?**

A new, independent, measurement will be most helpful here!

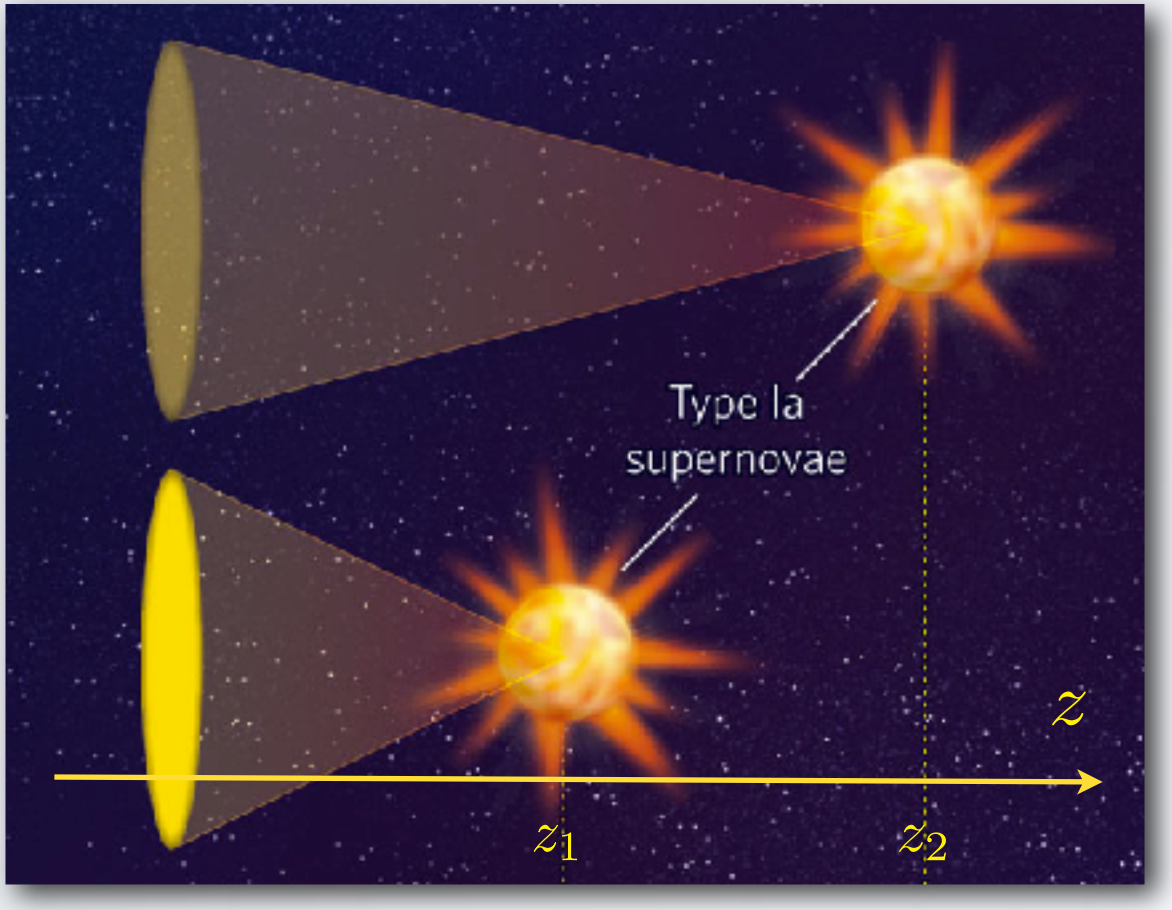


$$H \equiv \dot{a}/a \text{ , where } a = 1/(1+z)$$
$$H(z) = H_0 \cdot f(z; \Omega_m, \Omega_k, \Omega_{DE}, w_0, w_a)$$

ASTROPHYSICAL OBSERVABLES TO MEASURE DISTANCES

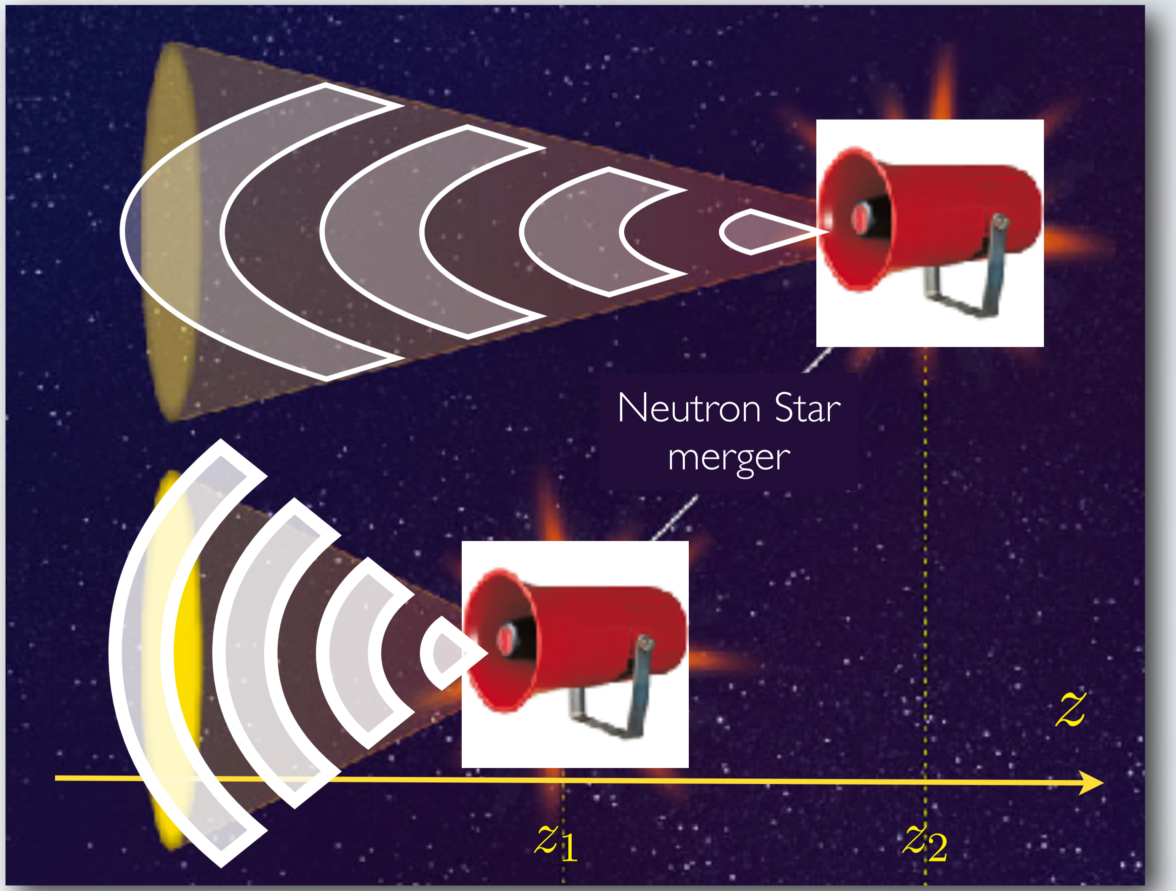
standard candle

Type Ia Supernovae (SNe)



standard siren

Binary Neutron Star mergers (BNS)
Binary Black Hole mergers (BBH)
Mixed mergers (NSBH)



DESGW: THE PROGRAM

Can we take advantage of this new way to observe the universe, with Gravitational Waves, to add a new Dark Energy probe to our repertoire and beat down the systematics? With this motivation, we launched the DESGW project in 2013.

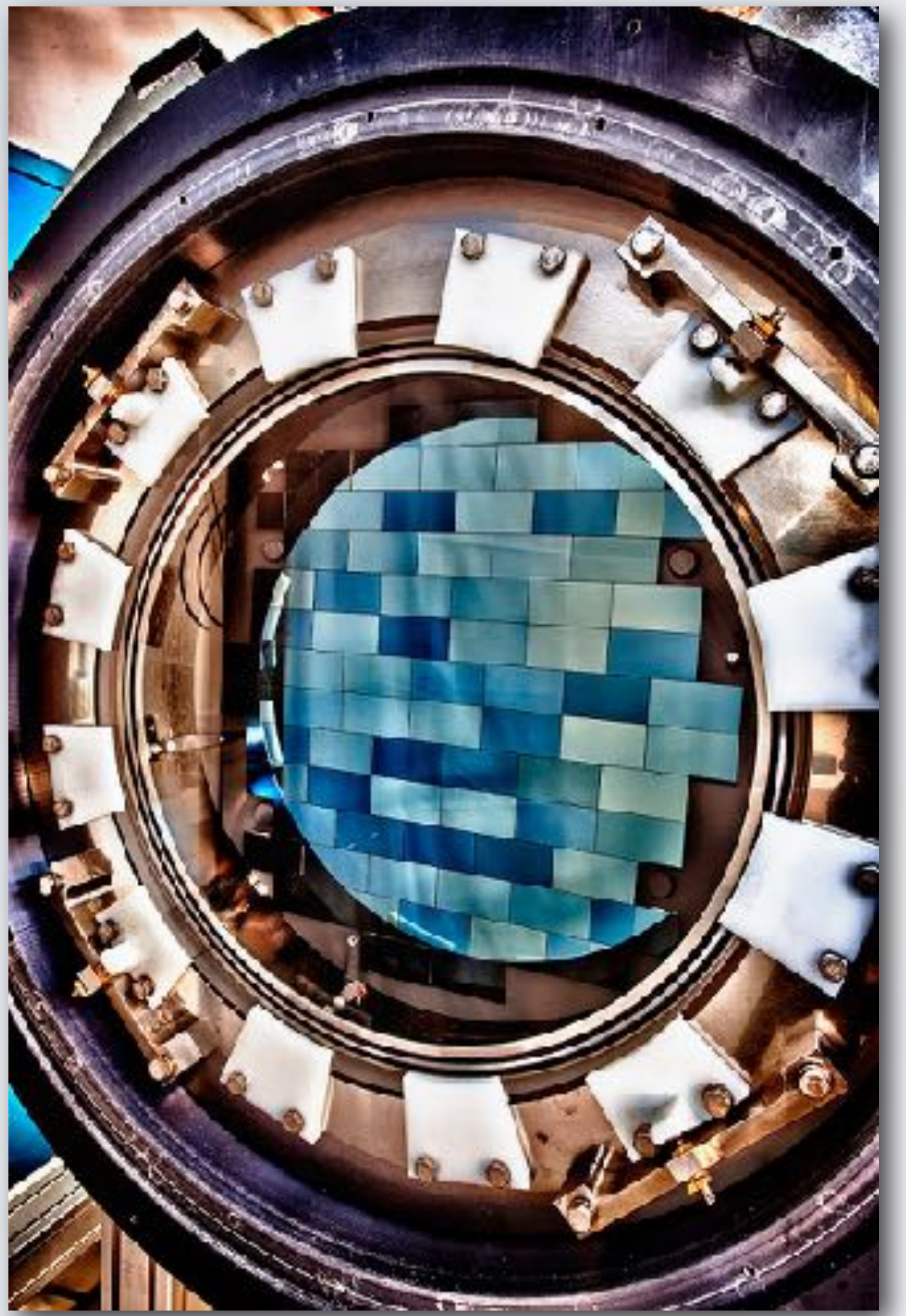
We obtained strong support from the DES Collaboration (Annis, Diehl, et al.) including experts from the SNe group (Kessler, Sako, Brout, Scolnic, Frieman, et al.).

We established a joint effort with LIGO members (Holz, Chen, Doctor, Farr) and non-DES DECam community users (Berger, Cowperthwaite et al.).

We developed an analysis that is sensitive to NS-NS, BH-NS mergers out to 400Mpc. We didn't see an optical counterpart in 2015-2016 run, but those results were encouraging. **This talk covers the results of the 2016-2017 run.**

Funding: Fermilab LDRD (FY15, FY16), UChicago SCI grant (FY17).
Telescope time: DECam nights (3 in 2015B, 5 in 2016B, 13 in 2017A, 3 in 2017B).

DARK ENERGY SURVEY



DECam

3 sq deg FOV, **570 Mpix** optical CCD camera

Facility instrument at **CTIO Blanco 4-m telescope in Chile**

First light: Sep 2012

DES programs

Wide: **5000 sq deg** grizY

SNe: **30 sq deg** SNe survey

GW: followup of **LIGO/Virgo events**

Neutrinos: followup of **Icecube events**

Goal to combine multiple Dark Energy Probes based on measurements of distance and growth of structures.

MIND THE GAPS!

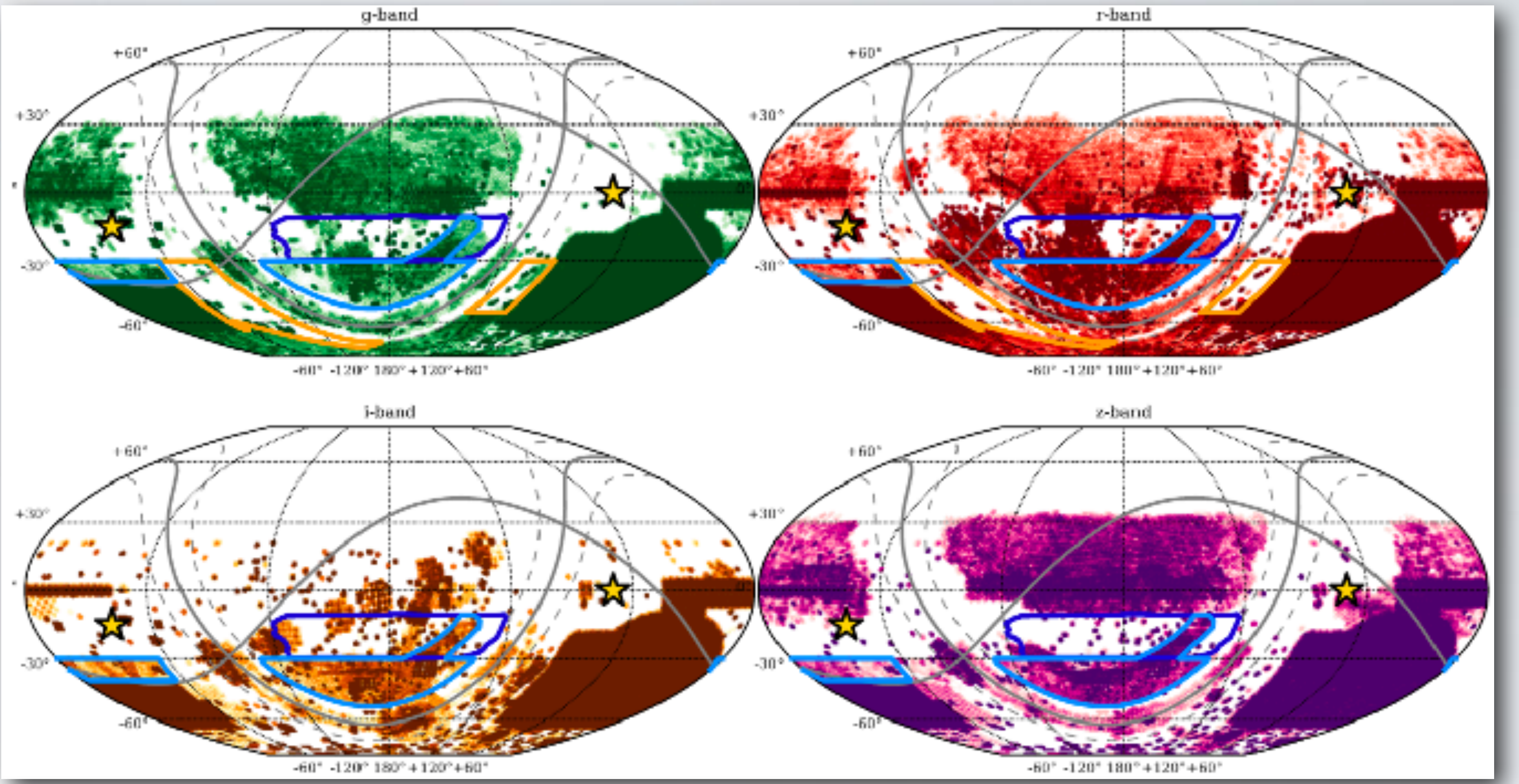
Blanco Images of the Southern Sky (BLISS)

Designed to complete the accessible sky coverage before LSST.

Science cases:
— GW
— Dwarf galaxies
— Planet 9

Pilot program: 10^3deg^2
11.5 nights in 2017A
(PIs: Soares-Santos, Drlica-Wagner)

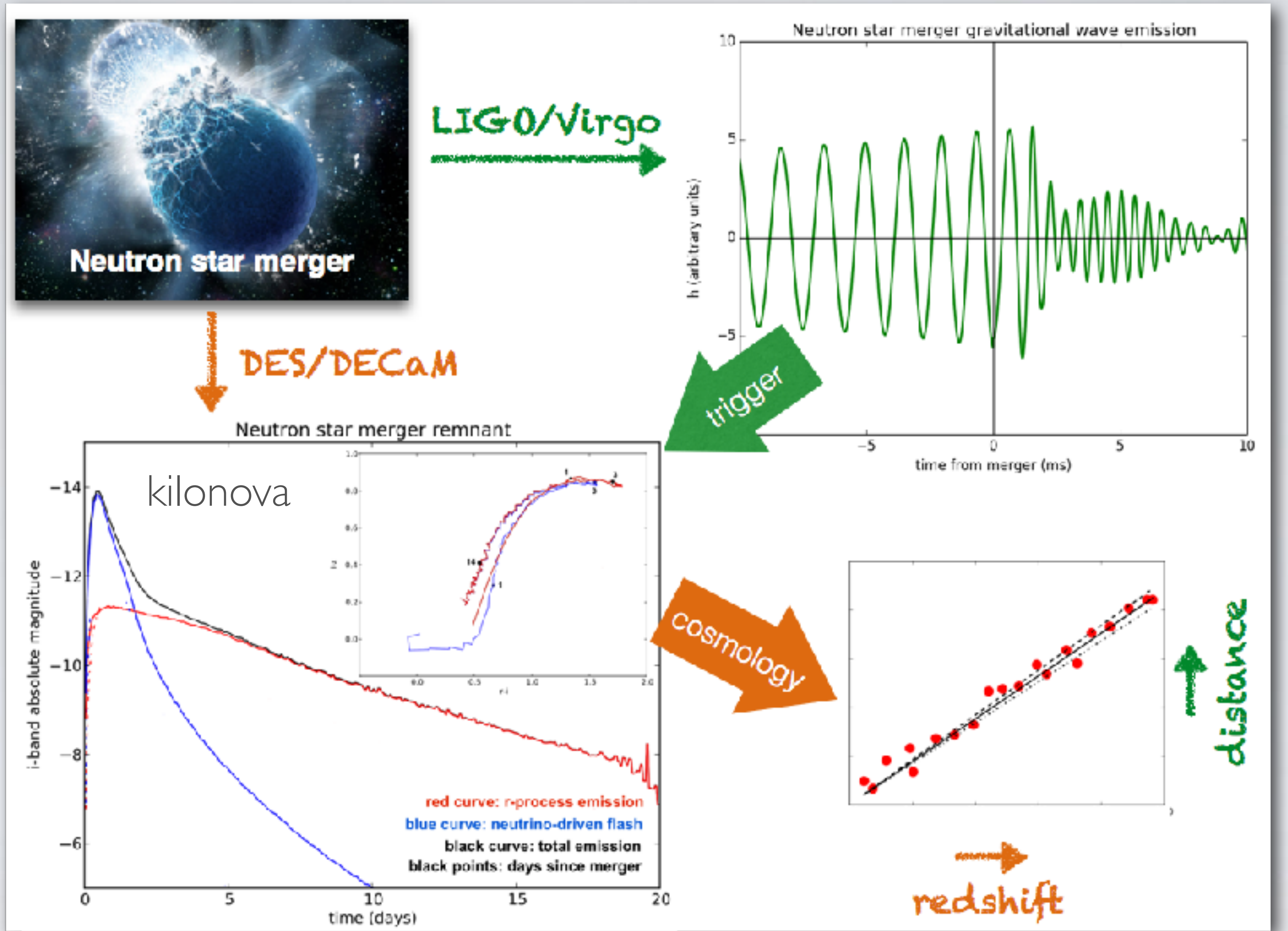
DECam sky coverage as of September 2017



Proposed for 2018A: 3,000 deg^2 (yellow stars)

Coordinating with MagLiteS and DeROSITAs

DESGW: A CARTOON



NS-NS MERGER EM SIGNATURES

Tidal forces cause the neutron star to drop from degenerate to normal state.

Neutrons then can convert; r-process nucleosynthesis

Small fraction of the total mass is ejected

Electromagnetic signatures:

— **short Gamma-Ray Burst**
— **kilonova (r-process)**
— **X-ray emission**
— **radio afterglow**

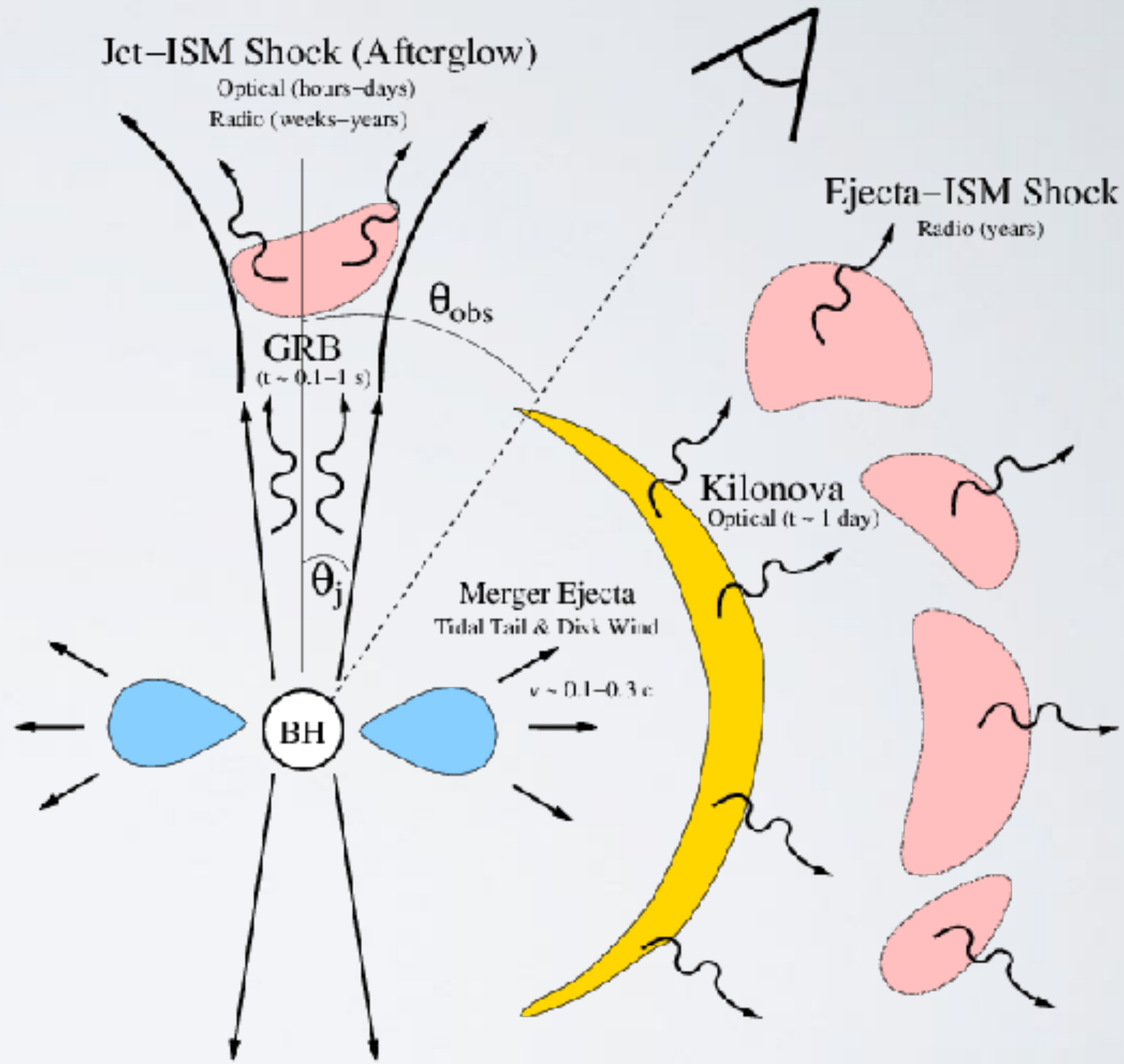
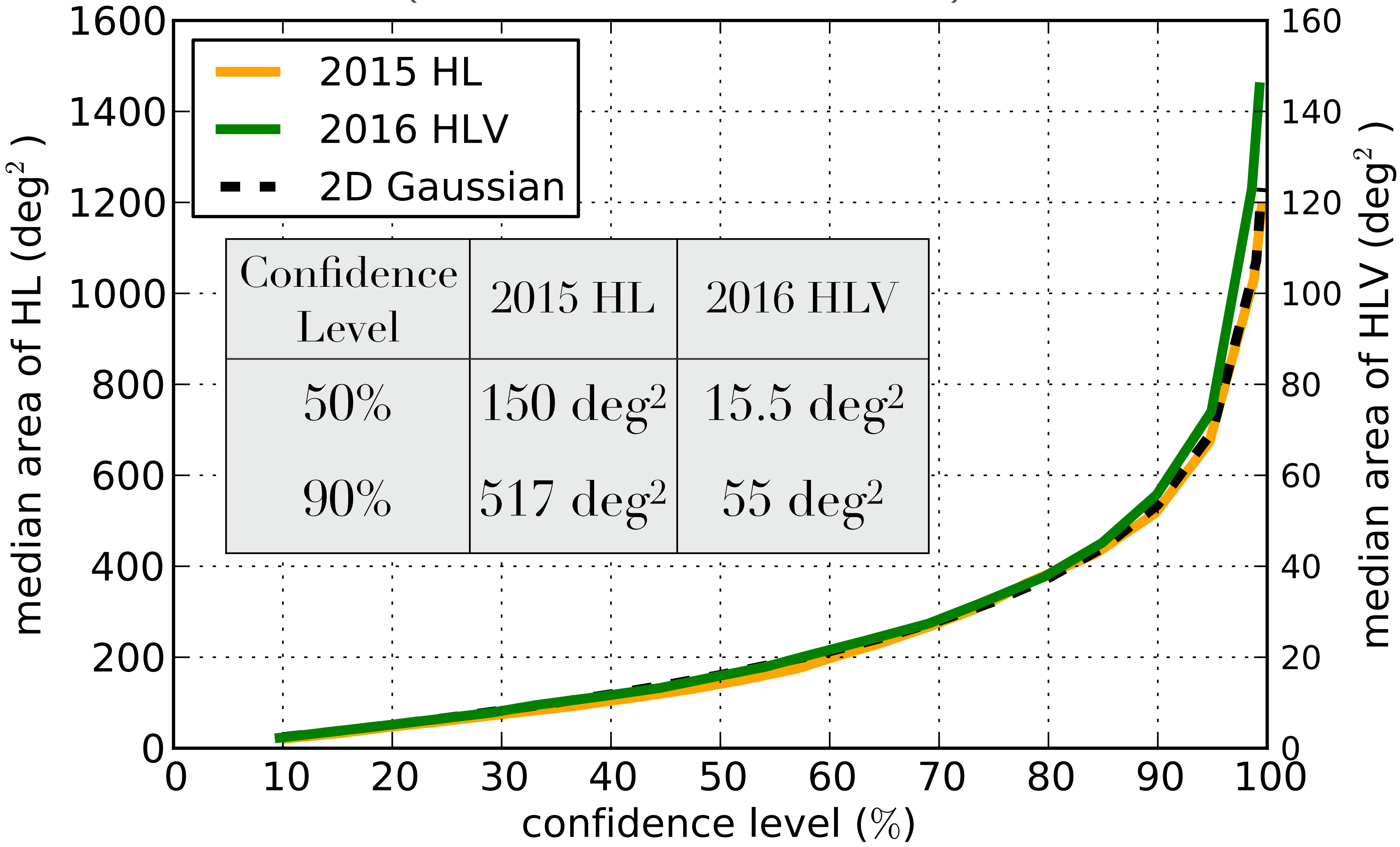


Figure: Metzger & Berger (arXiv: 1108.6056)

CHALLENGING SEARCH AREAS

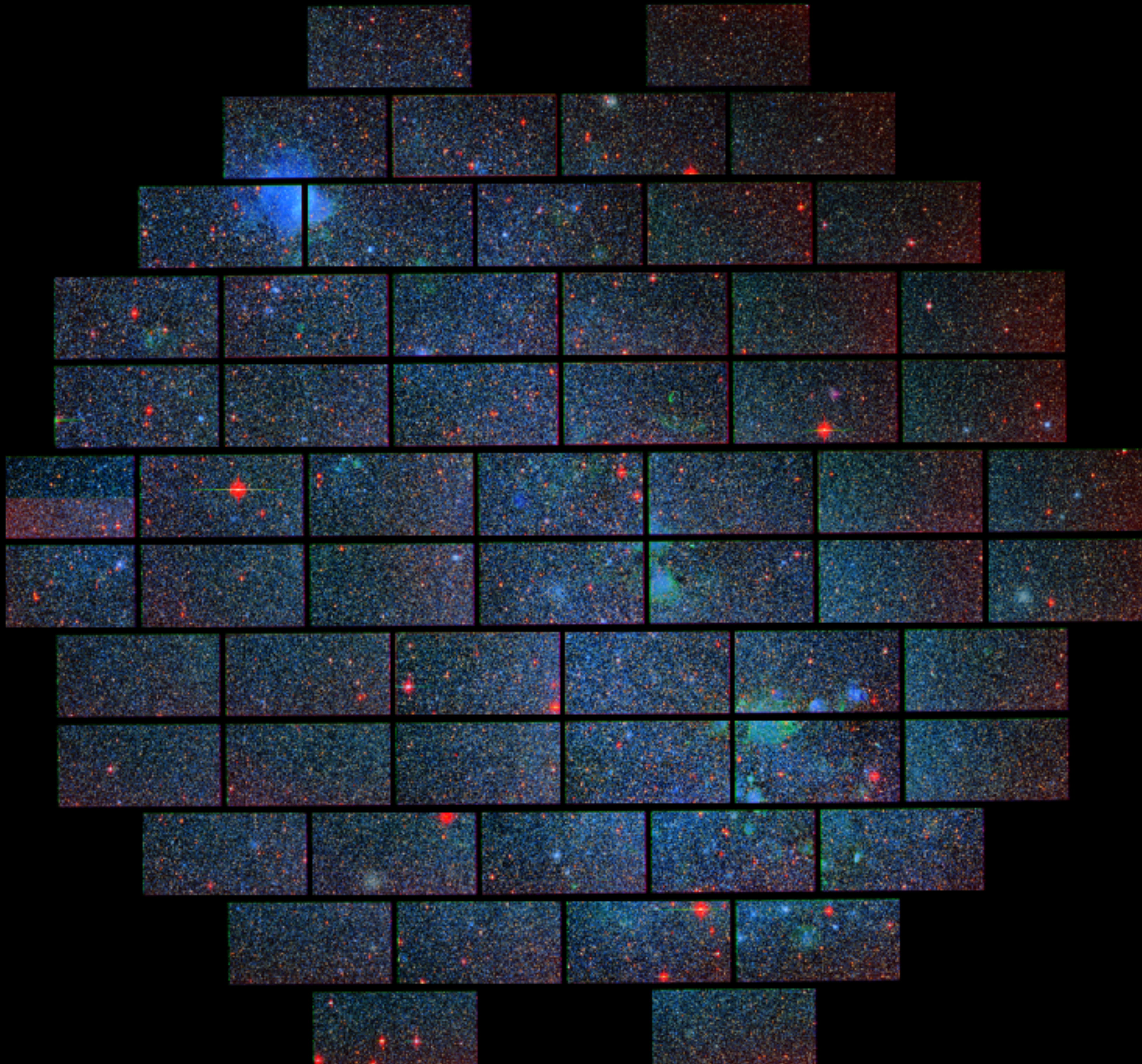
(Chen & Holz 2015)



Confidence Level	2015 HL	2016 HLV
50%	150 deg^2	15.5 deg^2
90%	517 deg^2	55 deg^2

BUT WE HAVE THE RIGHT INSTRUMENT…

3 square degree FOV on a 4-meter telescope!



The Small Magellanic Cloud, DES 1st light image, Sep 12 2012

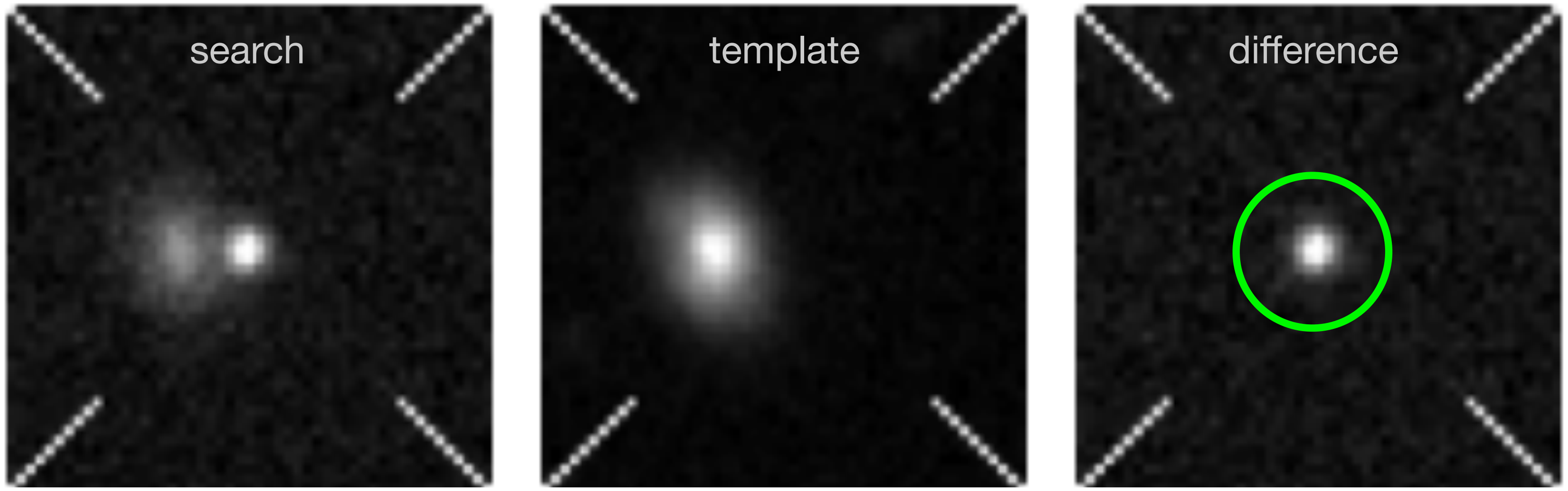
DIFFERENCE IMAGING

Each search image and template run through ***single epoch*** processing (~hrs each)

Then each CCD goes through ***difference imaging*** in parallel (~1hr/job)

Finally ***post-processing*** does assessment of outputs and creates the candidates list.

Example of transient source detected using the DES difference imaging pipeline. Template images (preferably taken before the search) are a crucial element of this program!



The Difference Imaging Pipeline for the Transient Search in the Dark Energy Survey

Kessler, et al. 2015, AJ, 150, 172

IMAGE PROCESSING WORKFLOW

Fermilab SCD project grew out of the LDRD initiative:

- Detect candidates via difference imaging (diffimg) within 24hours
- Run diffimg using GRID resources
- Machine learning algorithms applied to candidates to reject junk
- Detection efficiencies calculated by overlaying fake candidates on search images
- Post-processing to create analysis data products
- Details of the project described in Herner et al. 2016

DESGW 2015-2016 RESULTS

4. A search for Kilonovae in the Dark Energy Survey

Doctor, et al. arXiv:1611.08052, ApJ accepted

3. A DECam Search for an Optical Counterpart to the LIGO Gravitational Wave Event GW151226

Cowperthwaite, et al. 2016, ApJL, 826, 29

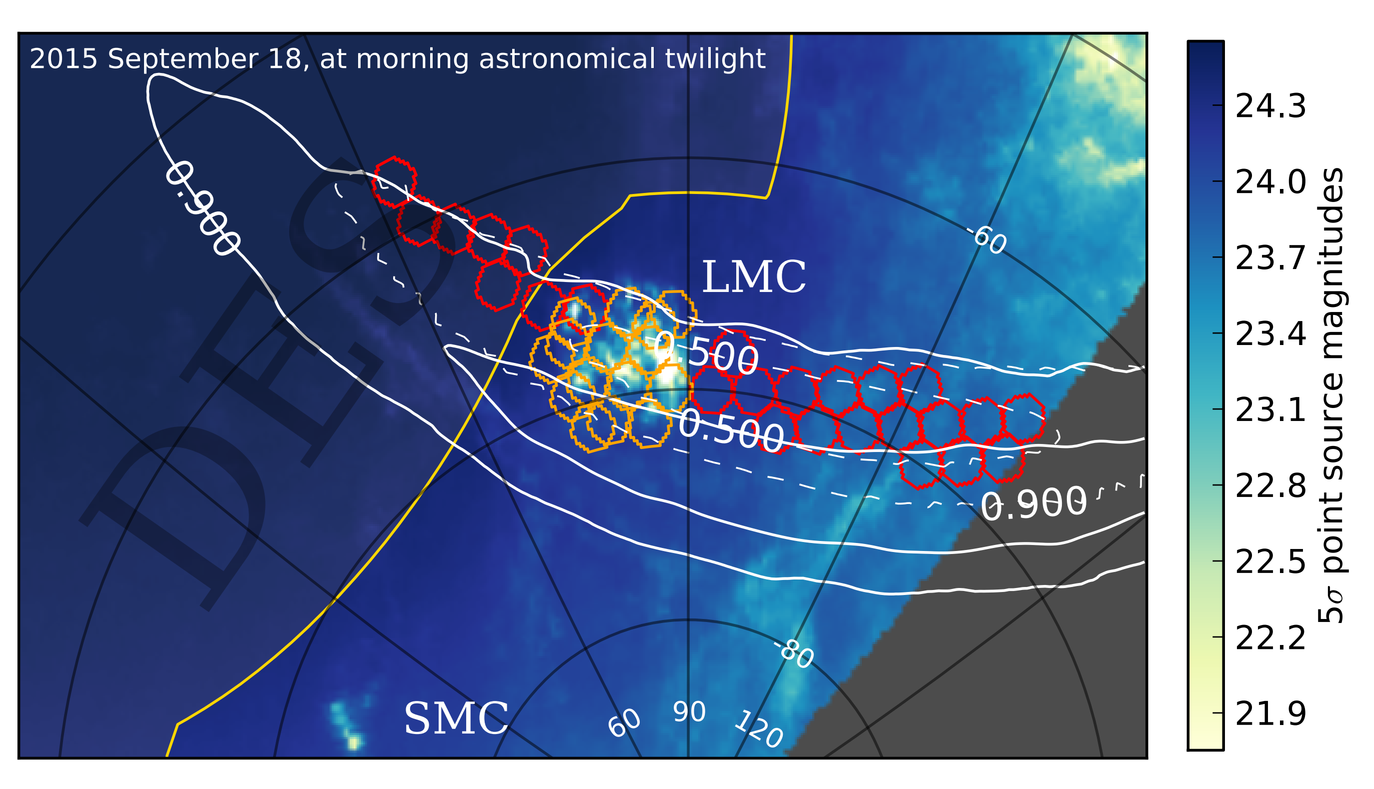
2. A Dark Energy Camera Search for Missing Supergiants in the LMC after the Advanced LIGO Gravitational Wave Event GW150914

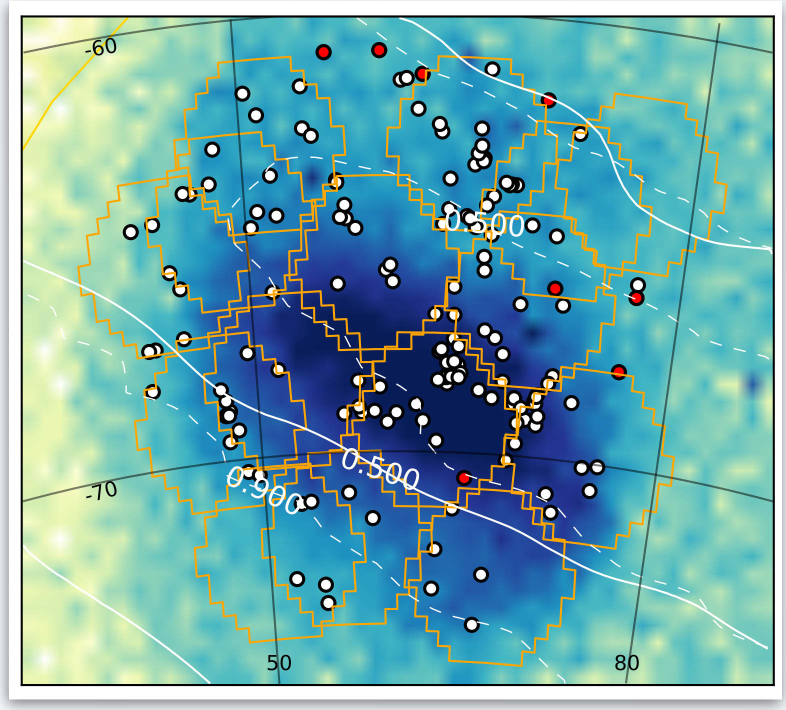
Annis, et al. 2016, ApJL, 823, 34

1. A Dark Energy Camera Search for an Optical Counterpart to the First Advanced LIGO Gravitational Wave Event GW150914

Soares-Santos, et al. 2016, ApJL, 816, 98

Soares-Santos et al. 2016





Annis et al. 2016

DESGW COSMOLOGY PROGRAM IN ACTION

The 1st Neutron Star merger event:
GW170817

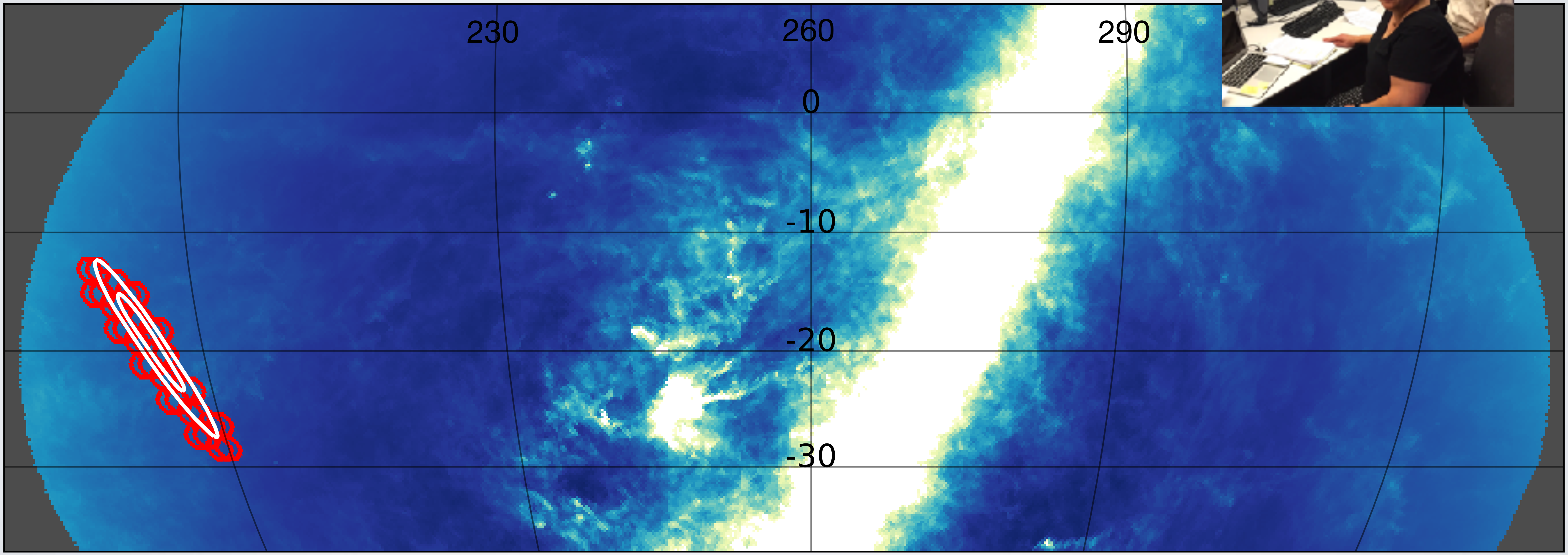
Trigger: Aug 17, 2017 at 07:41am Chicago time

A NEEDLE IN THE HAYSTACK

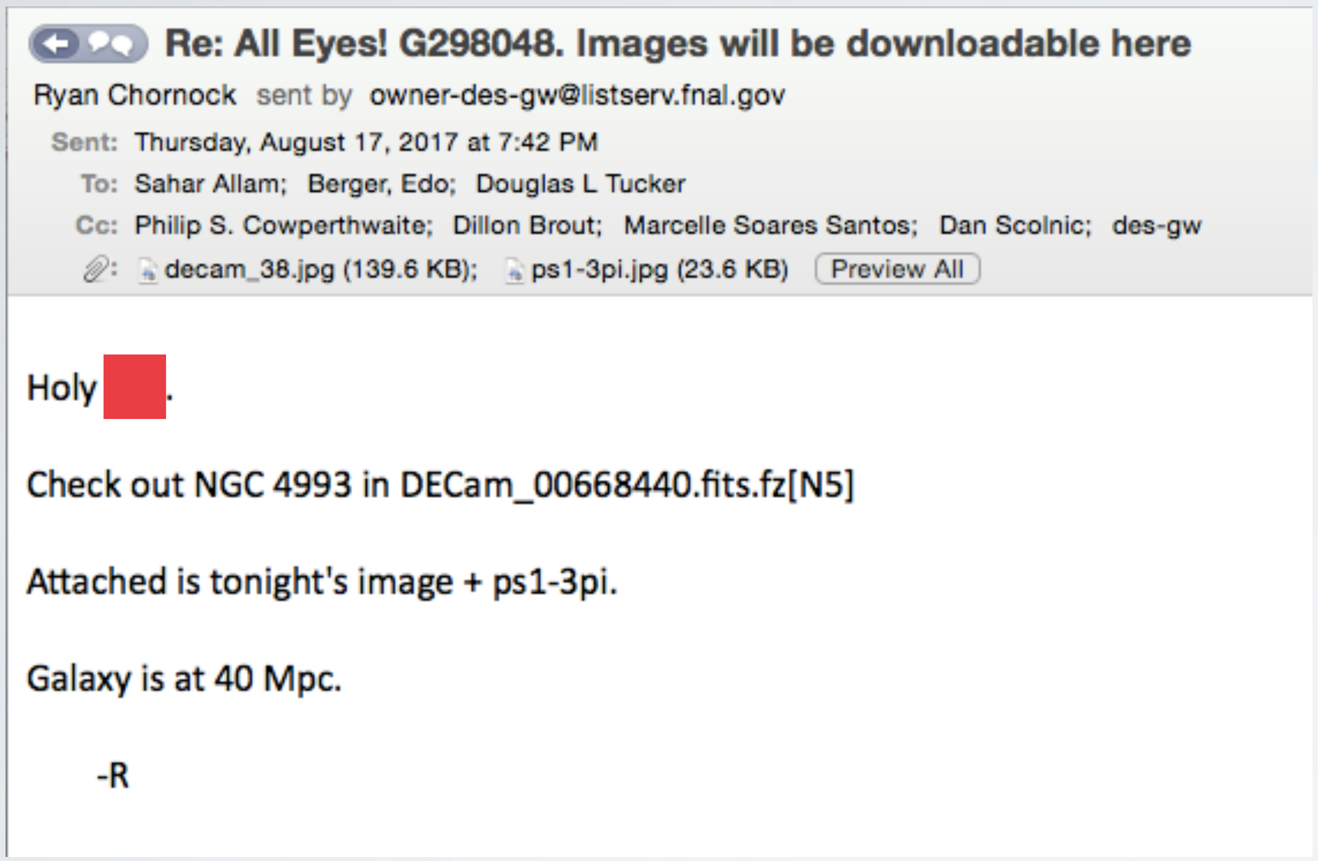
Localization region is in the far West and set ~1.5 hours after twilight.

Start observing as soon as it gets dark: 8:13 pm Chile time (23:13 UT), 10.5 hours after GW event.

Team in place to eyeball the images; Remote observing team at Fermilab



WE FOUND IT!


Re: All Eyes! G298048. Images will be downloadable here

Ryan Chornock sent by owner-des-gw@listserv.fnal.gov

Sent: Thursday, August 17, 2017 at 7:42 PM

To: Sahar Allam; Berger, Edo; Douglas L Tucker

Cc: Philip S. Cowperthwaite; Dillon Brout; Marcelle Soares Santos; Dan Scolnic; des-gw

decam_38.jpg (139.6 KB); ps1-3pi.jpg (23.6 KB) Preview All

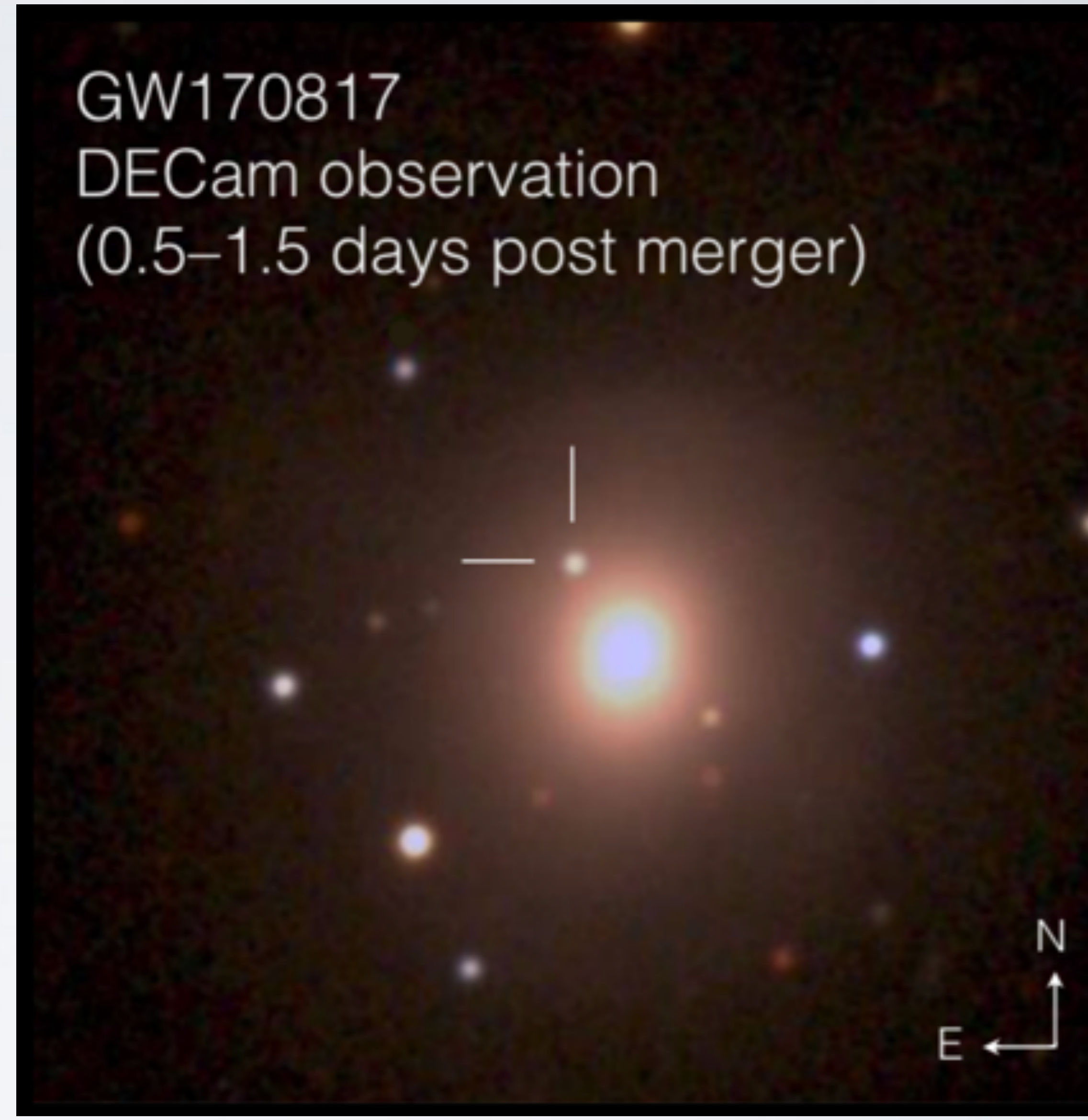
Holy [redacted].

Check out NGC 4993 in DECam_00668440.fits.fz[N5]

Attached is tonight's image + ps1-3pi.

Galaxy is at 40 Mpc.

-R

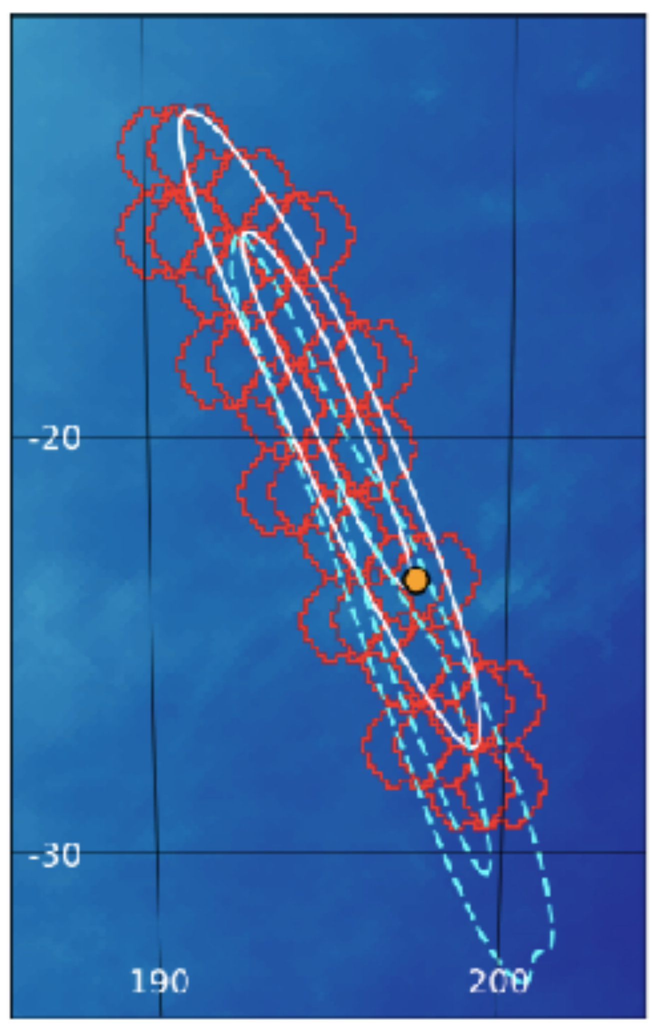


Several teams independently discovered the source within minutes from each other!
DESGW had the 2nd announcement to the network of teams.

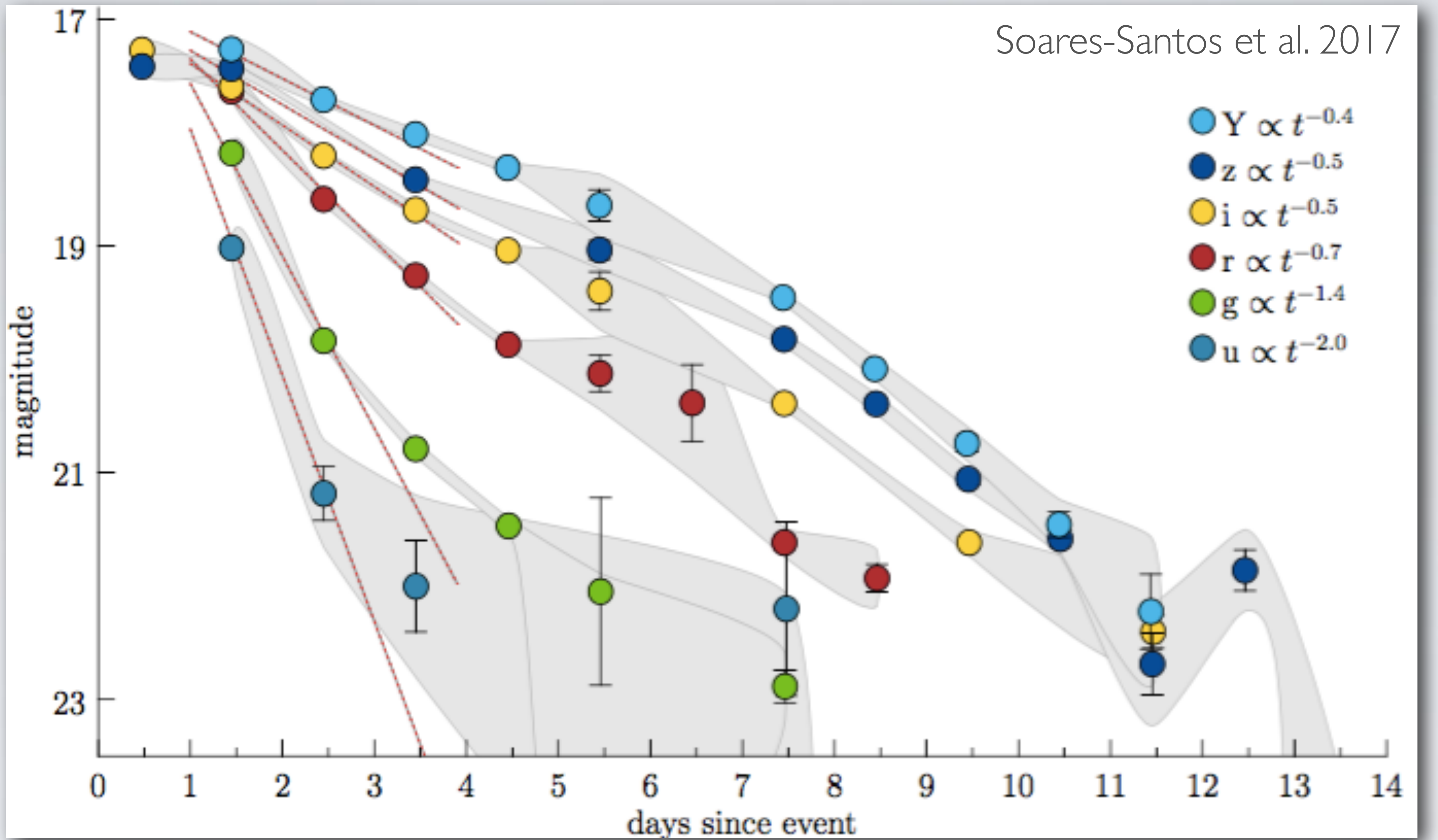
INDEPENDENT DISCOVERY OF OPTICAL TRANSIENT

Soares-Santos et al. 2017

1. DECam observations
   i. commenced at 10.5 hours past merger;
   ii. covered 70 sq-degrees to i<22, which in turn covers
      i. 93% of initial LIGO localization;
      ii. 80% of revised LIGO localization;
2. Located a source 11" away from NGC4993 with
   i. i=17.3 & z=17.5
   ii. M_i = -15.7 for H_0 = 70 km/s/Mac
3. Searching the entire area:
   i. 1500 transient candidates at i<20.5;
   ii. only one passes a set of simple cuts,
      i. require detection in i and z (n=1500-> 252),
      ii. pass machine learning junk rejection (252->81), &
      iii. faded by more than 3-sigma in 2 weeks (81->1).
   iii. The single remaining candidate is the one near NGC 4993.
4. Distance/redshift was not used in the analysis, therefore the redshift of the source can be used as an independent variable in the joint cosmological analysis.



COUNTERPART OBSERVATIONS



DECam light curve:

i. followed source in 6 filters for 2 weeks;

ii. three independent reductions;

iii. photometry good to 2%.

Simple implications:

i. bluer filters faded much faster than redder;

ii. for ~3 days consistent with cooling blackbody;

iii. peak of light curve ~1 day.

PROPERTIES OF THE SYSTEM

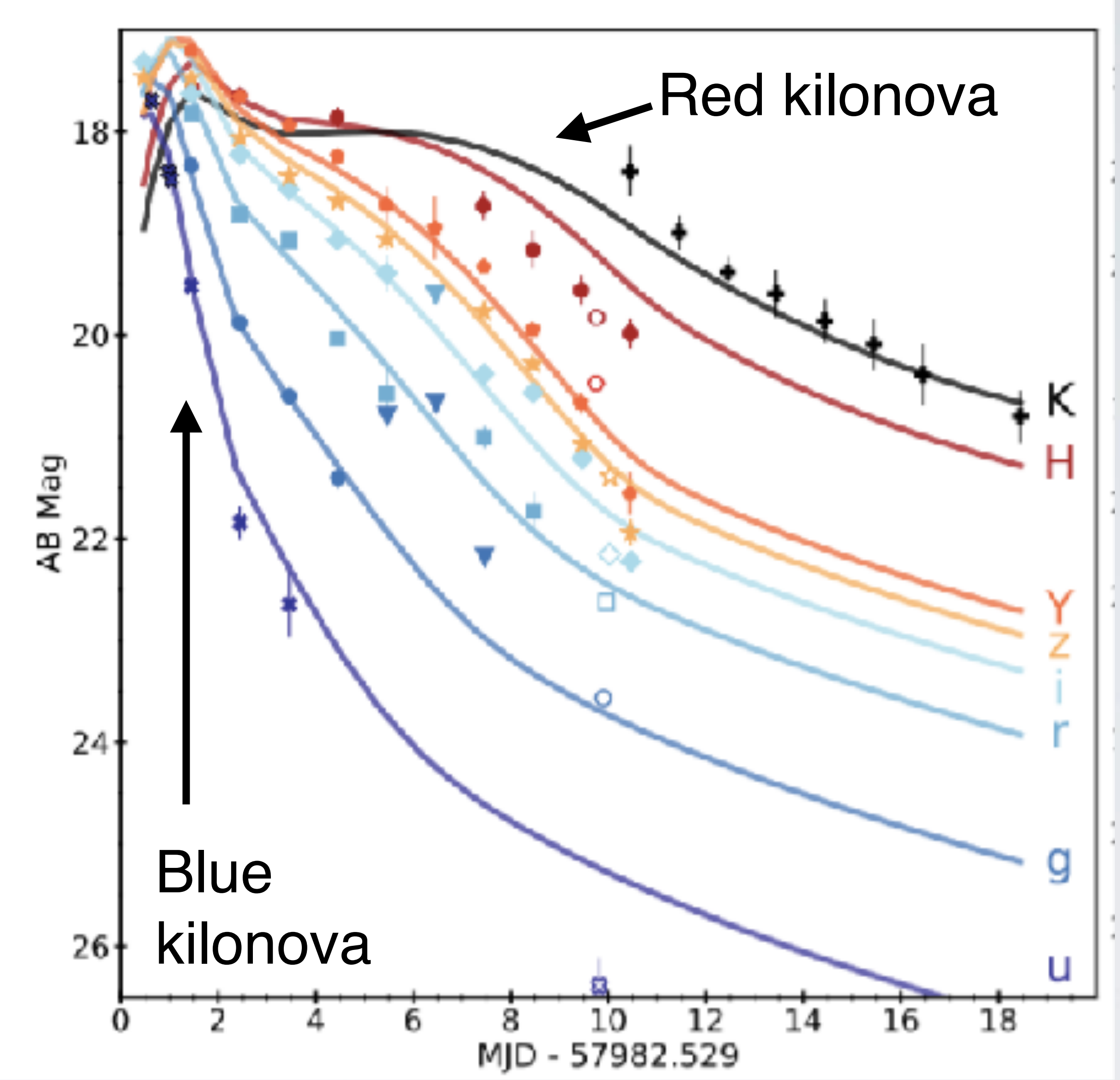
From the LIGO/Virgo data alone

date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely $\lesssim$ 14 km

A TWO-COMPONENT MODEL

1. Photometry
   i. DECam optical at day 0.5-10.5
   ii. Gemini NIR at days 1.5-18.5;
   iii. HST optical & NIR at day 9.8.
2. At day 0.6, the source has T ~ 8300K, which implies an expansion velocity of 0.3c.
3. The optical and infrared lightcurves can be modeled as 2 components, blue opacity fixed at 0.5 cm^2/gm, then:
   i. blue component:
      i. ejecta mass = 0.01 M_sun;
      ii. ejecta velocity = 0.3c;
   ii. red component:
      i. ejecta mass = 0.04 M_sun;
      ii. ejecta velocity = 0.1c;
      iii. opacity = 3.3 cm^2/gm.

Cowperthwaite et al. 2017



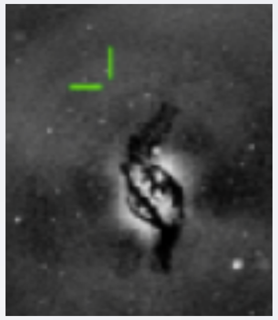
Blanco 4m telescope and DECam,
Gemini-South 8m Telescope and Flamingos-2 H&Ks, &
Hubble Space Telescope and WFC3 & ACS observations

THE MERGER ENVIRONMENT

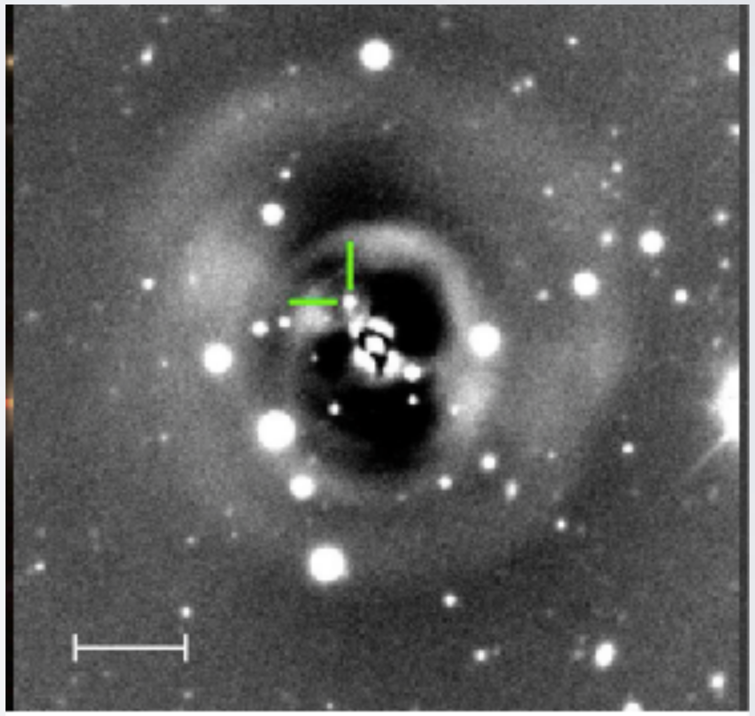
The host galaxy is an unremarkable elliptical galaxy, except…

1. **There is evidence NGC4993 suffered a merger with another galaxy**:
   i. DECam imaging shows shells, which the source is on or near;
   ii. HST imaging shows complex dust lanes in the center;
   iii. 6dF spectroscopy shows an AGN at the center.
2. Given the position of the shells and the velocity dispersion of NGC4993, the galaxy merger happened 25 Myr ago.
3. **Shell galaxies are indicative of minor mergers- the lesser galaxy < 10% of NGC4993 mass.**
4. The galaxy merger may have aided the formation of the neutron star binary system

Palmese et al. 2017



ACS

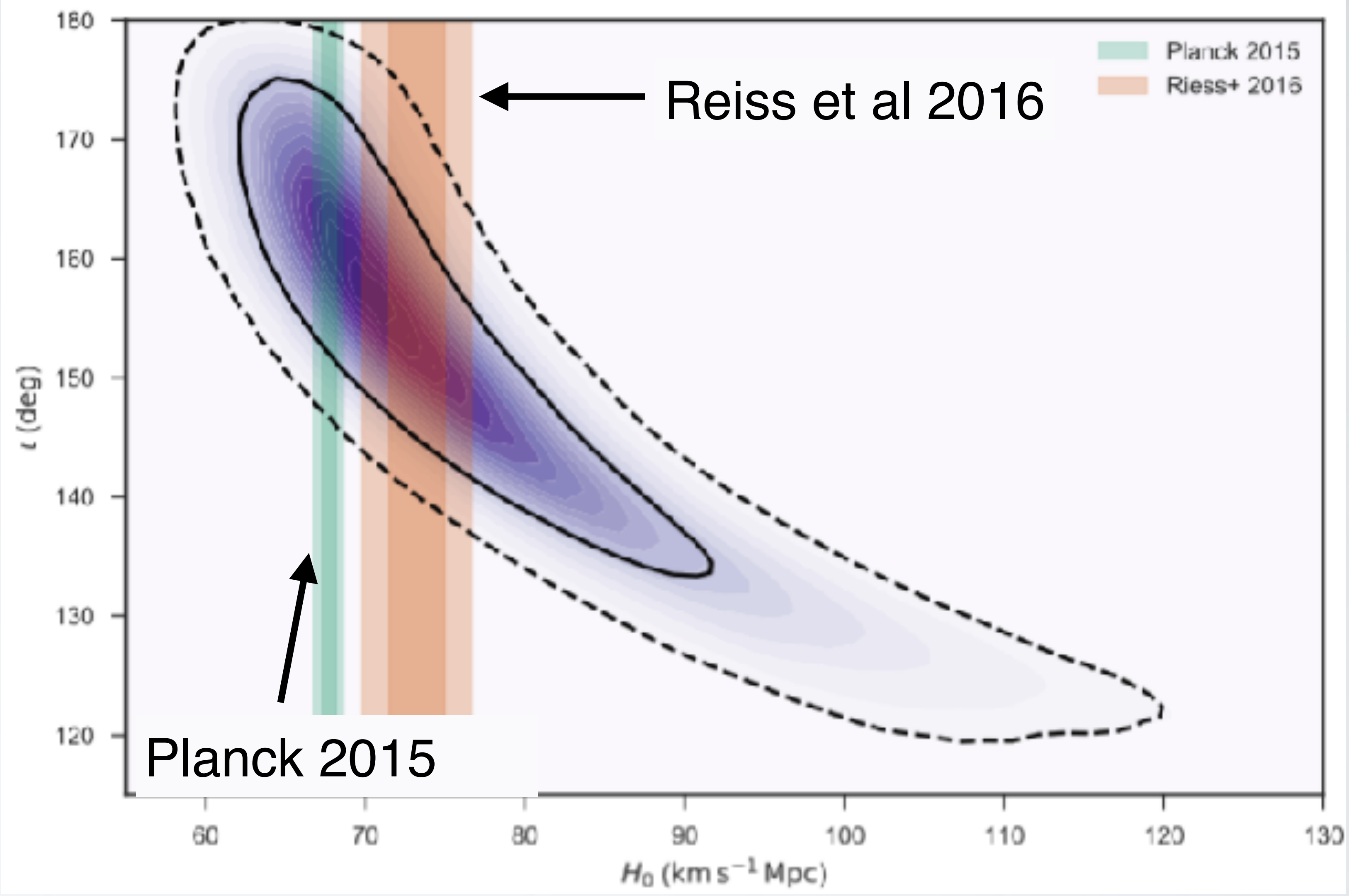


DECam

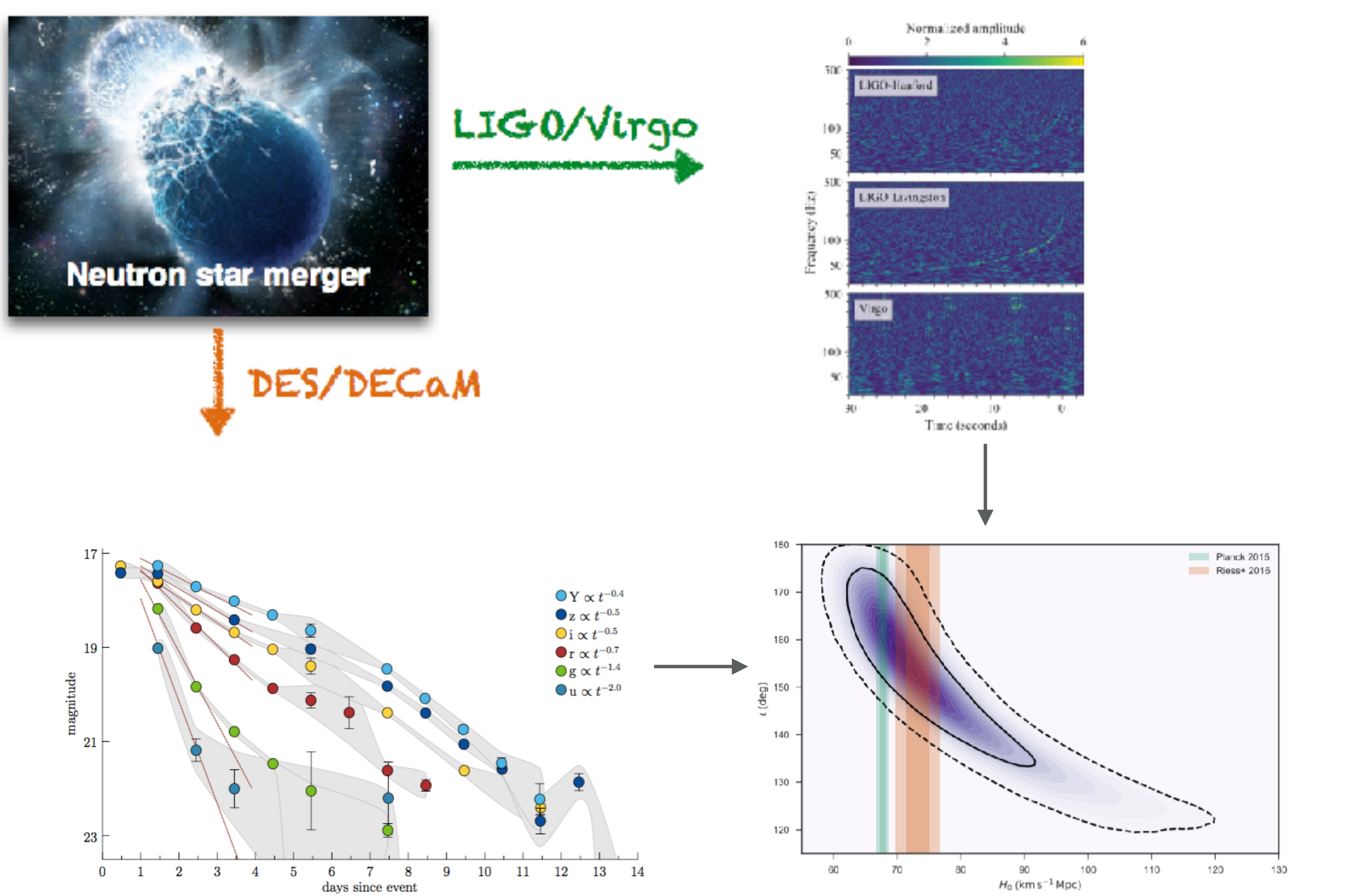
HUBBLE PARAMETER RESULT

LIGO/Virgo Collaboration et al. 2017
(including DESGW team)

1. GW waveform parameter estimation finds the distance to GW170817 to be
   i. d=39.7 +- 5.7 Mpc
   ii. 15% uncertainty due to noise, calibration, and inclination angle.
2. H_0 = cz/d where z is the Hubble flow
3. Determine velocity:
   i. group velocity = 3327 ±72km/s
   ii. groups can flow along filaments: estimate peculiar velocity using 8Mpc Gaussian kernel on 6dF peculiar velocity map (~10 glxs inside 1sigma),
   v_p = 304 ±68 km/s
   iii. Hubble flow velocity is
   v_H = 3010 ±95 km/s
4. $H_0 = 69.3^{+12}_{-6}$ km/s/Mpc, independent of both the distance ladder (cephieds) and inverse distance ladder (BAO/CMB)



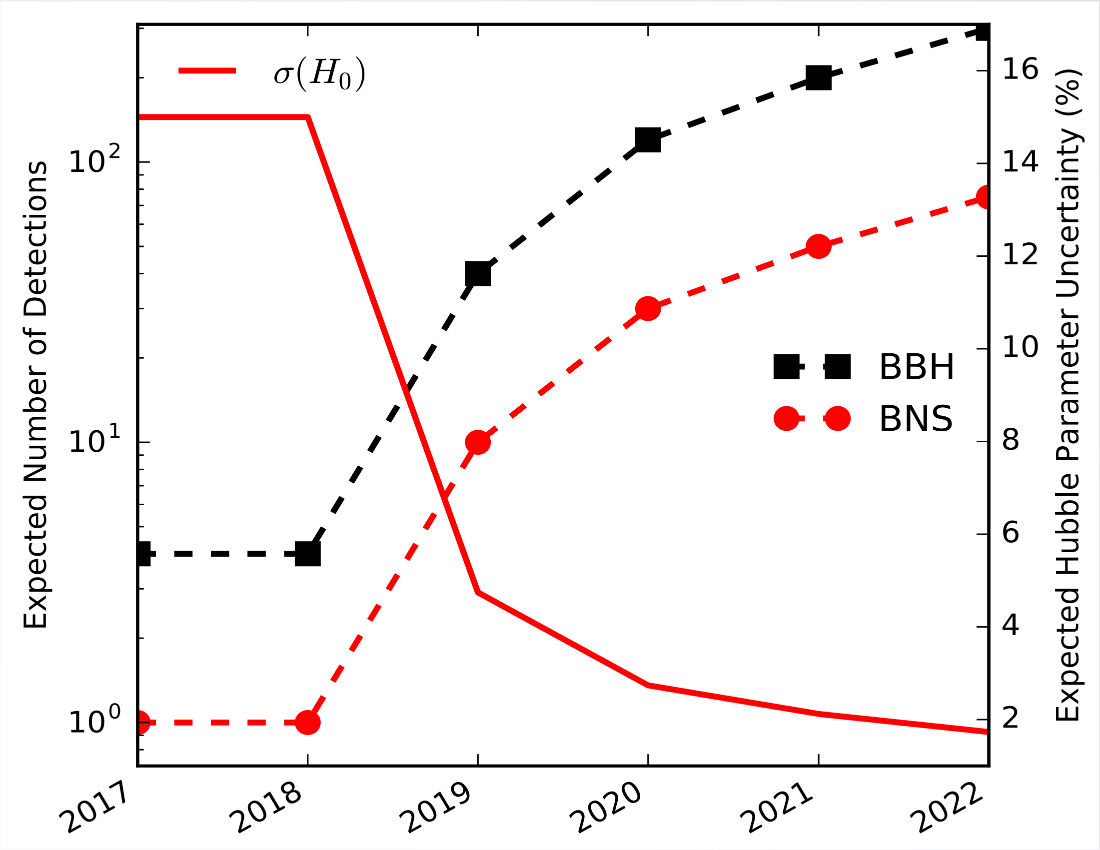
DESGW: BEYOND A CARTOON!



Soares-Santos et al. 2017 LIGO/Virgo et al. 2017

FUTURE PROSPECTS

- Can use "Dark" (BBH) and "Bright" (BNS, NS-BH) Standard Sirens to measure H_0
  - Bright: Distance from GW component; redshift from EM component $cz = H_0 d$
    - **Independent** measurement from SNe, CMB results; no cosmic distance ladder
- Roughly 3% precision with ~20 BNS events
- 1-2% precision possible in the LSST era
  - LSST already thinking about transient science
  - Now's the time to apply the lessons from DES!
    - Observation economics, systematics...



These are exciting times for science with the **Dark Energy Survey** & **Gravitational Waves**.

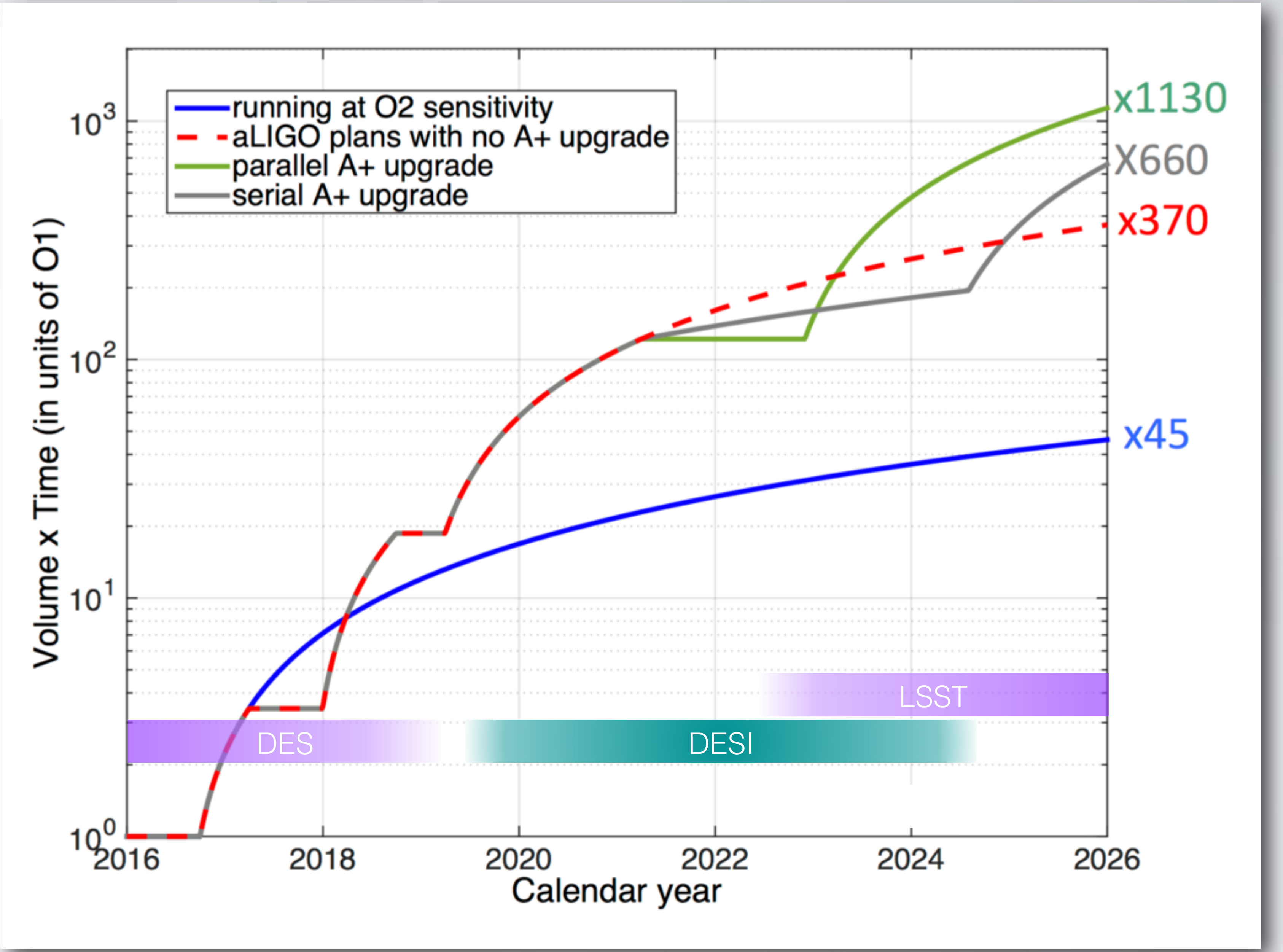
DECam enabled us to participate on the discovery of the first neutron star merger with an associated electromagnetic counterpart, **inaugurating the golden era of multi-messenger astronomy**, and **blazing a new trail for cosmology**.

BACKUP

THE ERA OF GW ASTRONOMY

The outstanding LIGO results from the first observing run (O1) have inaugurated a new era of gravitational wave astronomy:
2 black hole mergers!

Many more detections are expected in the coming years. That's a very exciting prospect!



Plot from the DAWN-2016 workshop report.

DATA

28 fields, izz bands, 90 sec (11 in footprint, 17 outside)
20 fields, izz bands, 5 sec (LMC area)

Program	Night	MJD	Δt^{a} (days)	$\langle$PSF(FWHM$_i$)$\rangle$ (arcsec)	$\langle$airmass$\rangle$	$\langle$depth$_i\rangle$ (mag)	$\langle$depth$_z\rangle$ (mag)	$A_{\mathrm{eff}}{}^{b}$ (deg^2)
Main, 1st epoch	2015-09-17	57383	3.88	1.38	1.50	22.71	22.00	52.8
	2015-09-18	57384	4.97	1.35	1.46	22.82	22.12	14.4
Main, 2nd epoch	2015-09-20	57286	6.86	2.17	1.51	22.18	21.48	67.2
Main, 3rd epoch	2015-10-07	57303	23.84	1.46	1.40	22.33	21.63	67.2
LMC, initial	2015-09-17	57383	3.98	1.14	1.30	21.32	20.62	14.4
LMC, extension	2015-09-26	57292	12.96	1.21	1.28	20.91	20.21	33.6

ANALYSIS 1

Search for a decaying transient (Soares-Santos et al. 2016)

Area (square degrees)

Total observed: 102
Excluding LMC: 84
Considering fill-factor: 67
Good after diffimg: 40
(~30% loss due to missing templates)

Sample selection
(all cuts in i and z bands)

0) Good detection in 1st epoch
1) 2nd epoch S/N>2
2) 3+ sigma 1st to 2nd epoch flux decline
3) S/N < 3 sigma in the 3rd epoch

Efficiency estimates from simulated events

decay rate: 0.3 mag/day
50% recovery rate depth:

color: (i-z) ~ 1 i = 21.5
color: (i-z) ~ 0 i = 21.1
color: (i-z) ~-1 i = 20.1

Sensitive to typical NS-NS mergers out to 200Mpc.

ANALYSIS I

Search for a decaying transient (Soares-Santos et al. 2016)

Result

Zero candidates pass our selection criteria. No optical signatures are predicted for BBH events, so this is not surprising.

Sample selection (all cuts in i and z bands)

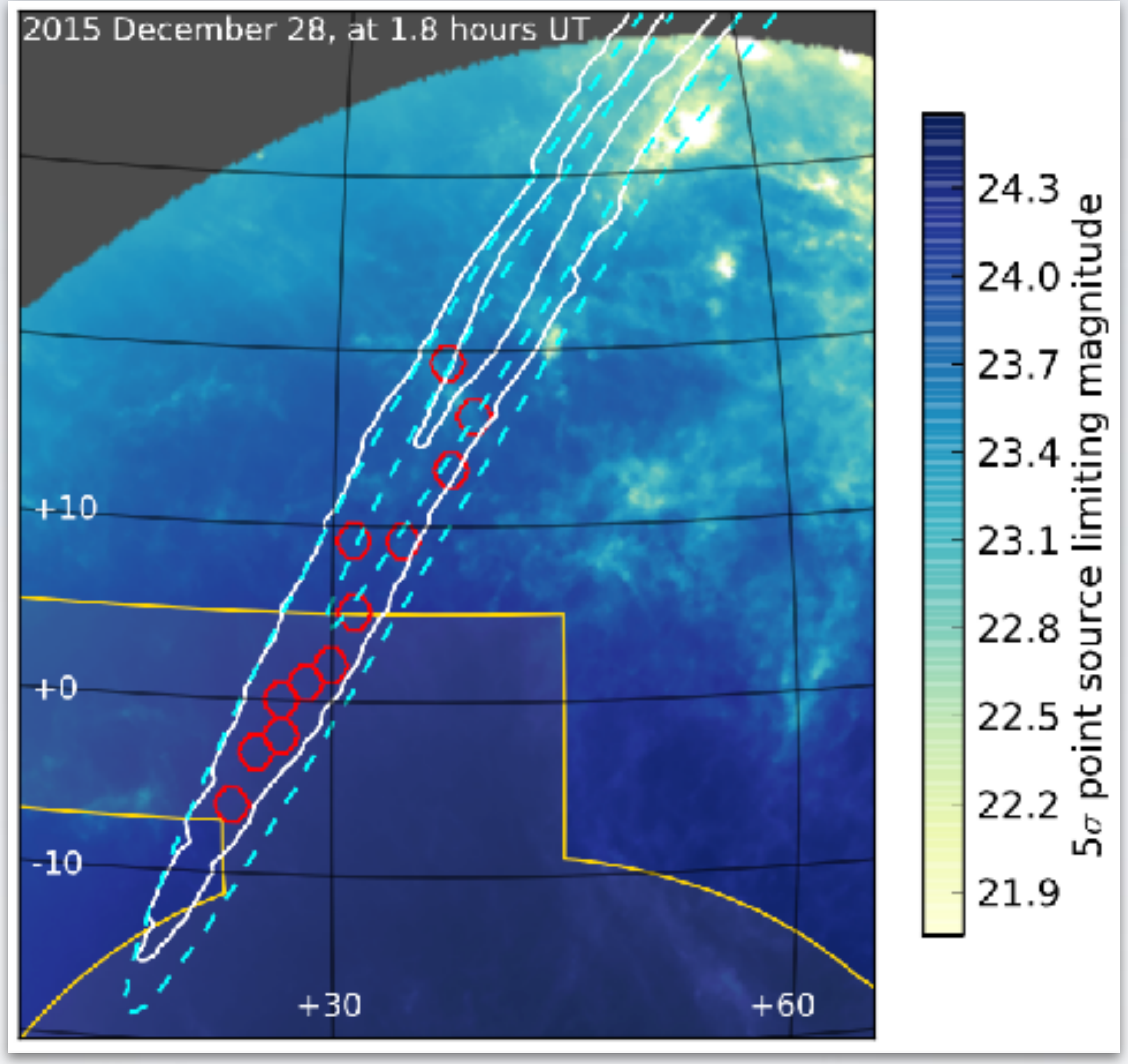
0) Good detection in 1st epoch
1) 2nd epoch S/N>2
2) 3+ sigma 1st to 2nd epoch flux decline
3) S/N < 3 sigma in the 3rd epoch

NUMBER OF SELECTED EVENTS

mag(i)	raw	cut 1	cut 2	cut 3
18.0–18.5	84	1	0	0
18.5–19.0	177	1	0	0
19.0–19.5	291	2	0	0
19.5–20.0	227	2	1	0
20.0–20.5	156	17	2	0
20.5–21.0	225	42	3	0
21.0–21.5	334	84	2	0
21.5–22.0	756	159	1	0
22.0–22.5	1099	183	0	0
total	2349	491	9	0

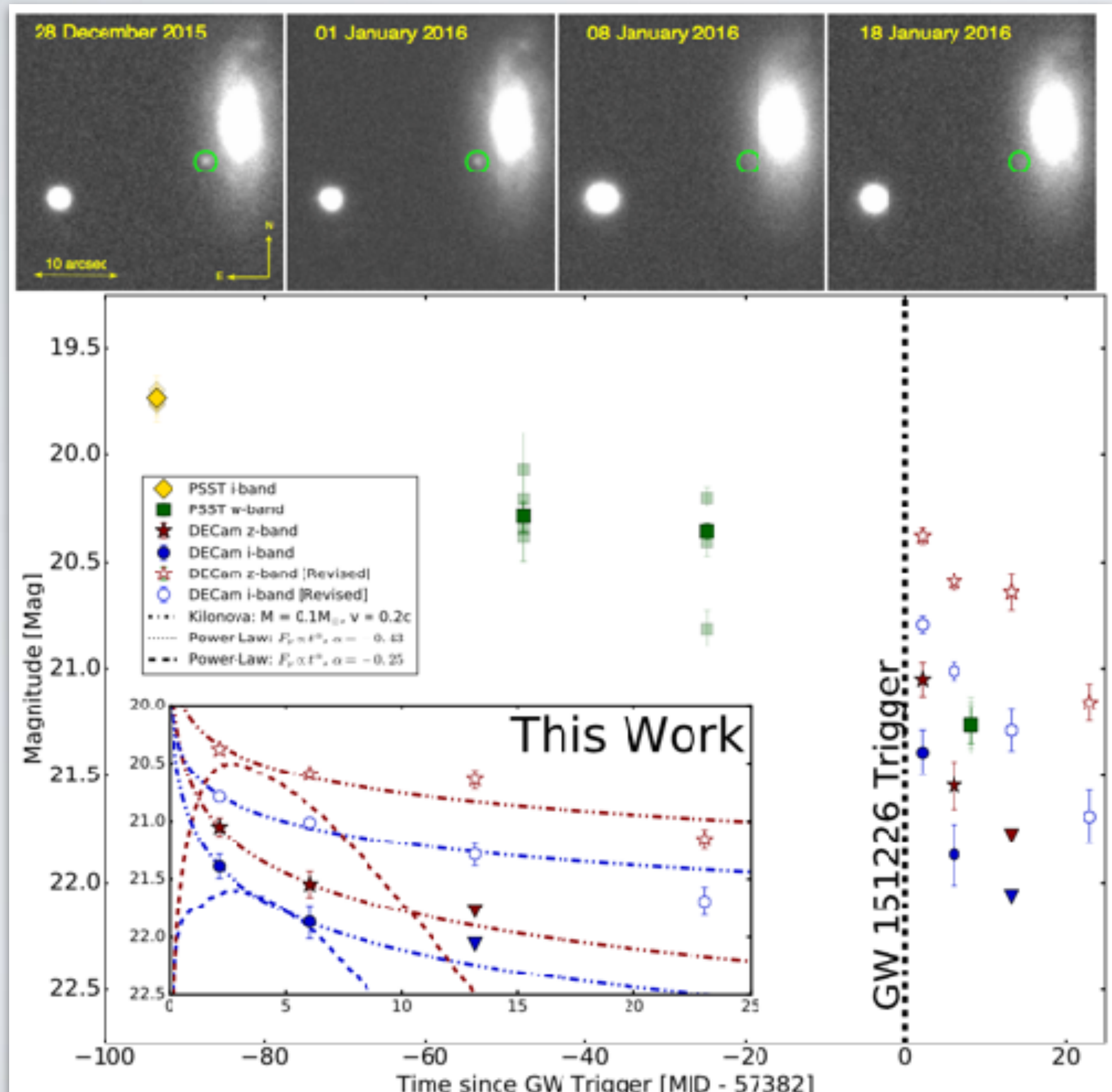
This type of search is a starting point for future NS-NS merger searches.

EVENT #2 – GW151226



ANALYSIS 3

Search for a decaying transient (Cowperthwaite et al. 2016)



36 square degrees observed (28.8 if considering fill-factor)

4 epochs (last one is template)

4 "candidates" (3 AGNs, 1 SN)

Pre-existing templates would have helped reject those.
It is really important to have pre-existing templates!

Rising portion of light curve helps too.
Need to observe ASAP after a trigger!

UPGRADES FOR O2, PROSPECTS

Developed separate ***observing strategies*** for

— ***bright*** sirens (mergers with at least one neutron star)

— ***dark*** sirens (e.g. binary black holes, for which we have no EM model)

Improved our ***processing times*** to ~24h and prepared to engage ***spectroscopic*** and ***multi-wavelength*** resources to confirm candidates.

Started gathering ***more templates***, with ***BLISS***.

The second observing campaign (O2) has just ended (on Aug 25). Analyses are underway and results will be made public soon.

In the long run, we want to combine ~10 good detections to obtain a measurement with 3% uncertainty or better.

— That will allow us to contribute to the Hubble parameter debate and set the stage for percent-level precision with LSST in the 2022 and beyond!

DES GW RESULTS SUMMARY

4. A search for Kilonovae in the Dark Energy Survey

Doctor, et al. arXiv:1611.08052, ApJ accepted

*3. A DECam Search for an Optical Counterpart to the LIGO Gravitational Wave Event GW151226

Cowperthwaite, et al. 2016, ApJL, 826, 29

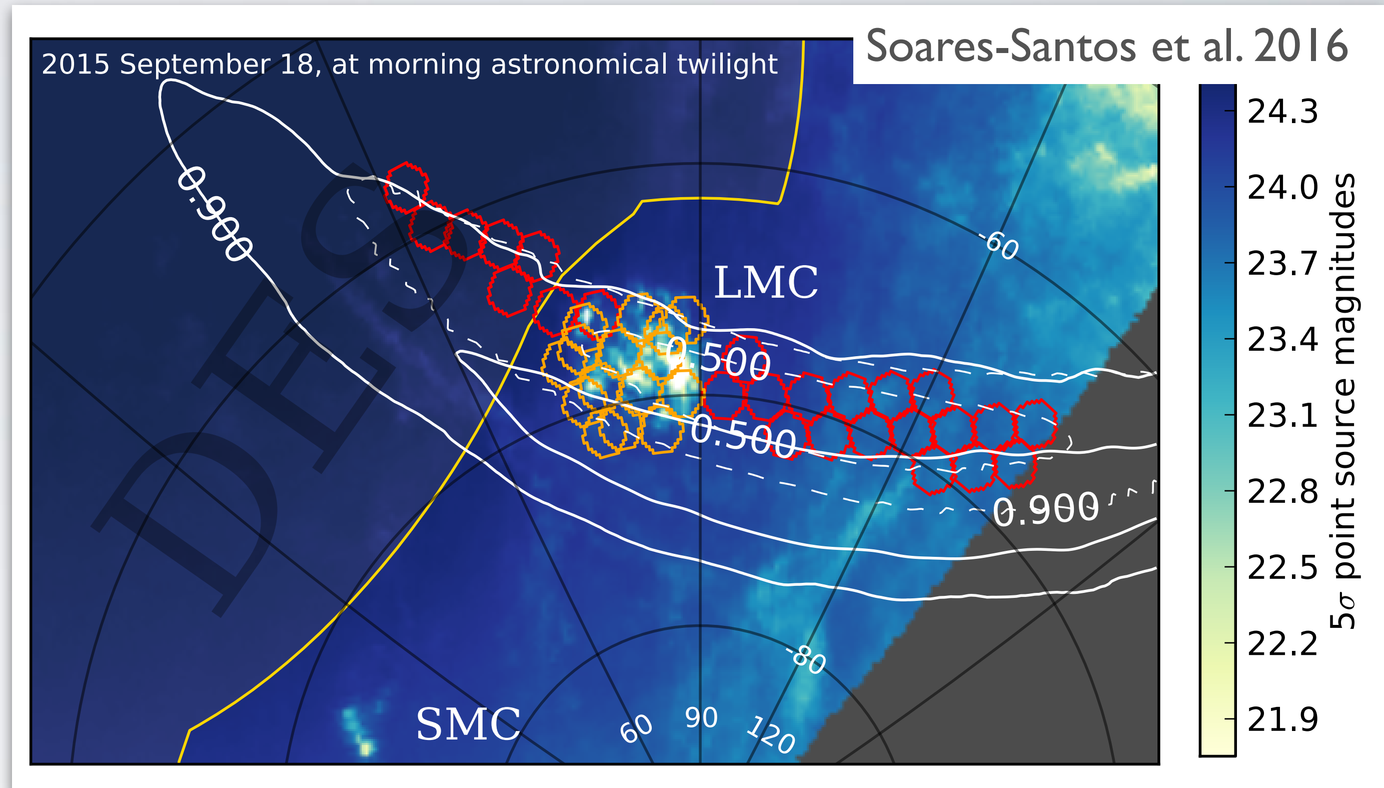
2. A Dark Energy Camera Search for Missing Supergiants in the LMC after the Advanced LIGO Gravitational Wave Event GW150914

Annis, et al. 2016, ApJL, 823, 34

*1. A Dark Energy Camera Search for an Optical Counterpart to the First Advanced LIGO Gravitational Wave Event GW150914

Soares-Santos, et al. 2016, ApJL, 816, 98

(*In this talk.)



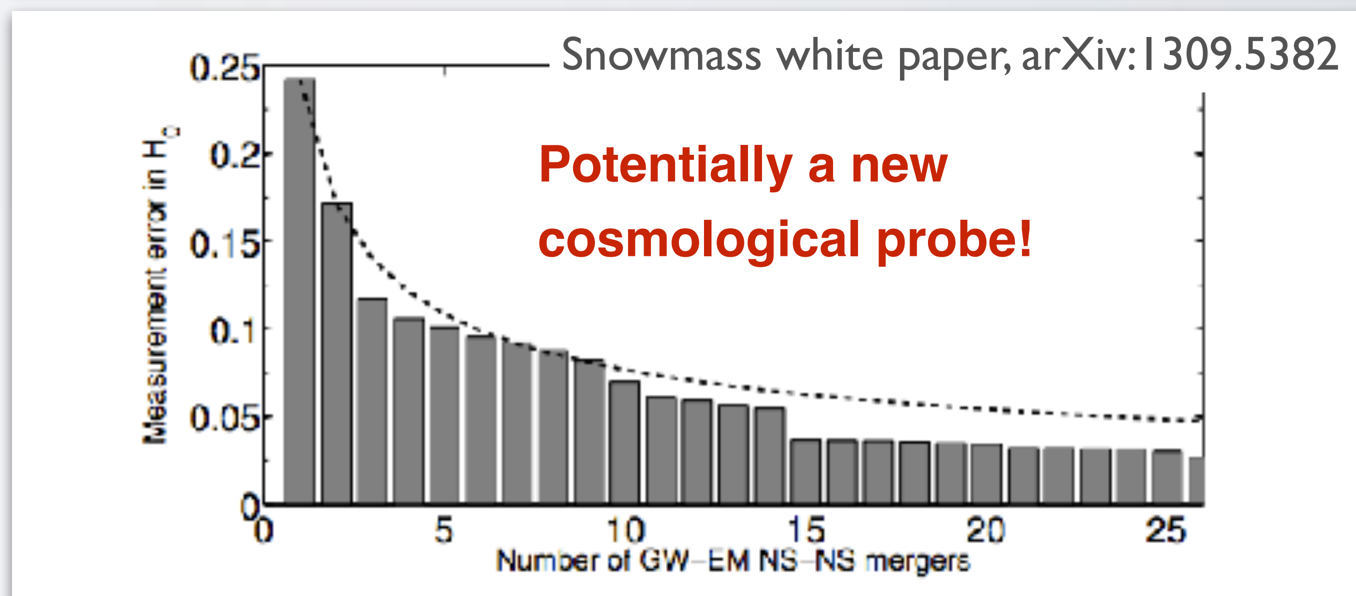
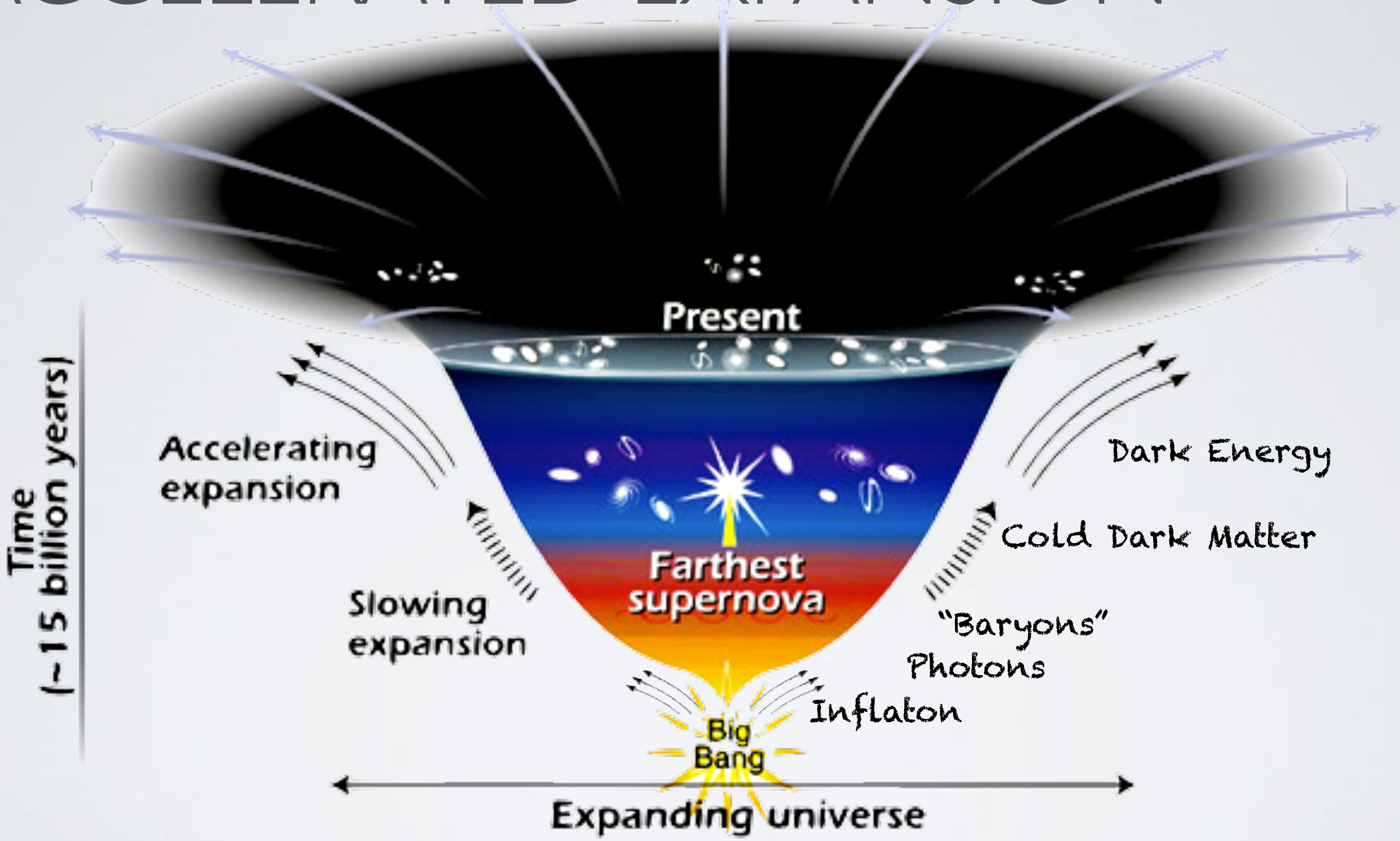


Figure 8: H_0 measurement uncertainty as a function of the number of multi-messenger (GW+EM) double neutron star merger events observed by an advanced LIGO-Virgo network. The dashed line shows Gaussian convergence.

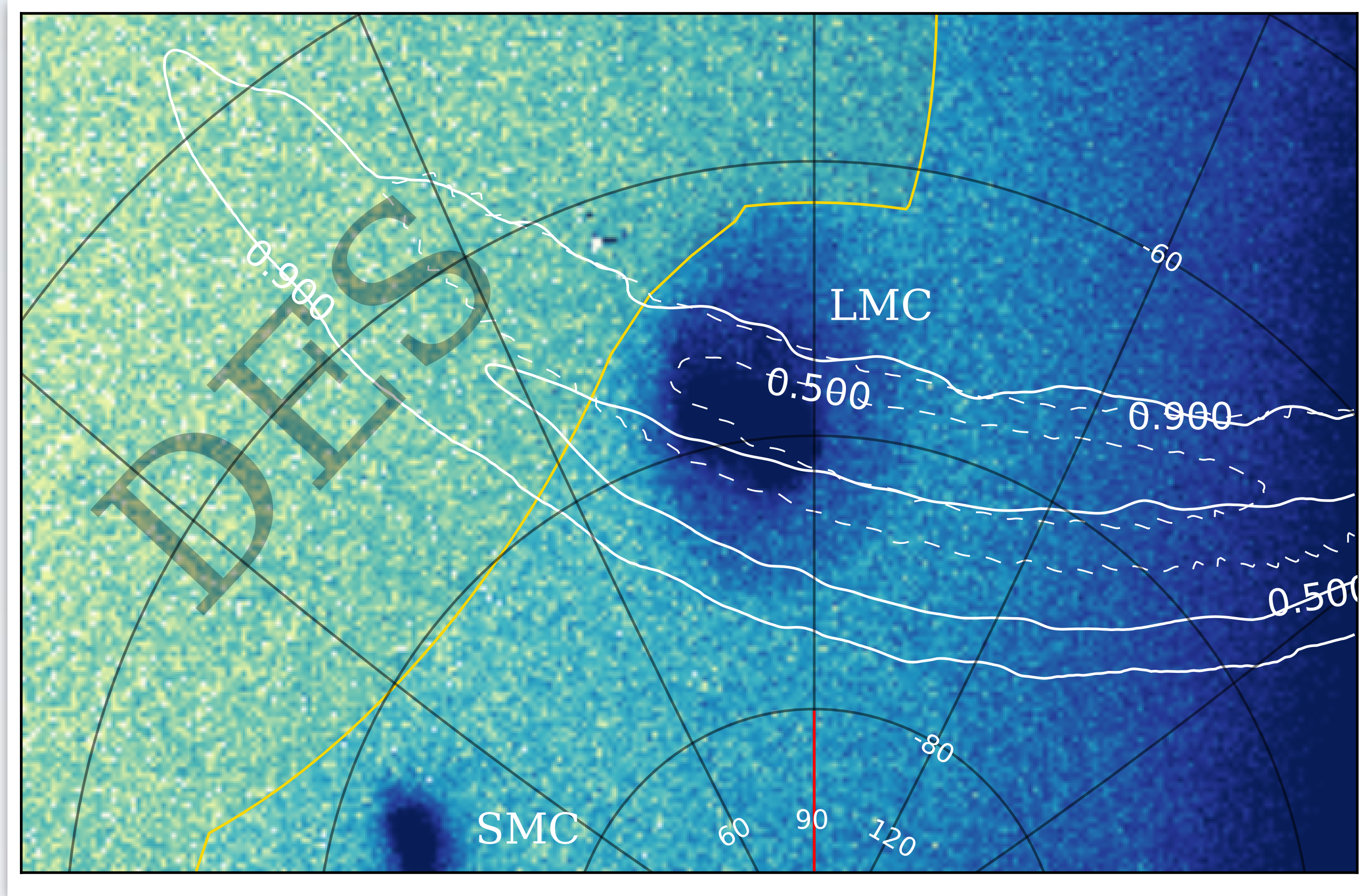
DARK ENERGY & ACCELERATED EXPANSION



ANALYSIS 2

Search for disappearing stars in the LMC (Annis et al. 2016)

GW150914 was *initially* thought to be a burst event, and could be due to a core-collapse (CC) nearby.



CC's often result in supernova explosions (e.g. 1987A), but none were reported in the LMC at the time.

~ 20% of the CC's are expected to fail to produce supernovae.
Could GW150914 be associated with a failed SNe?

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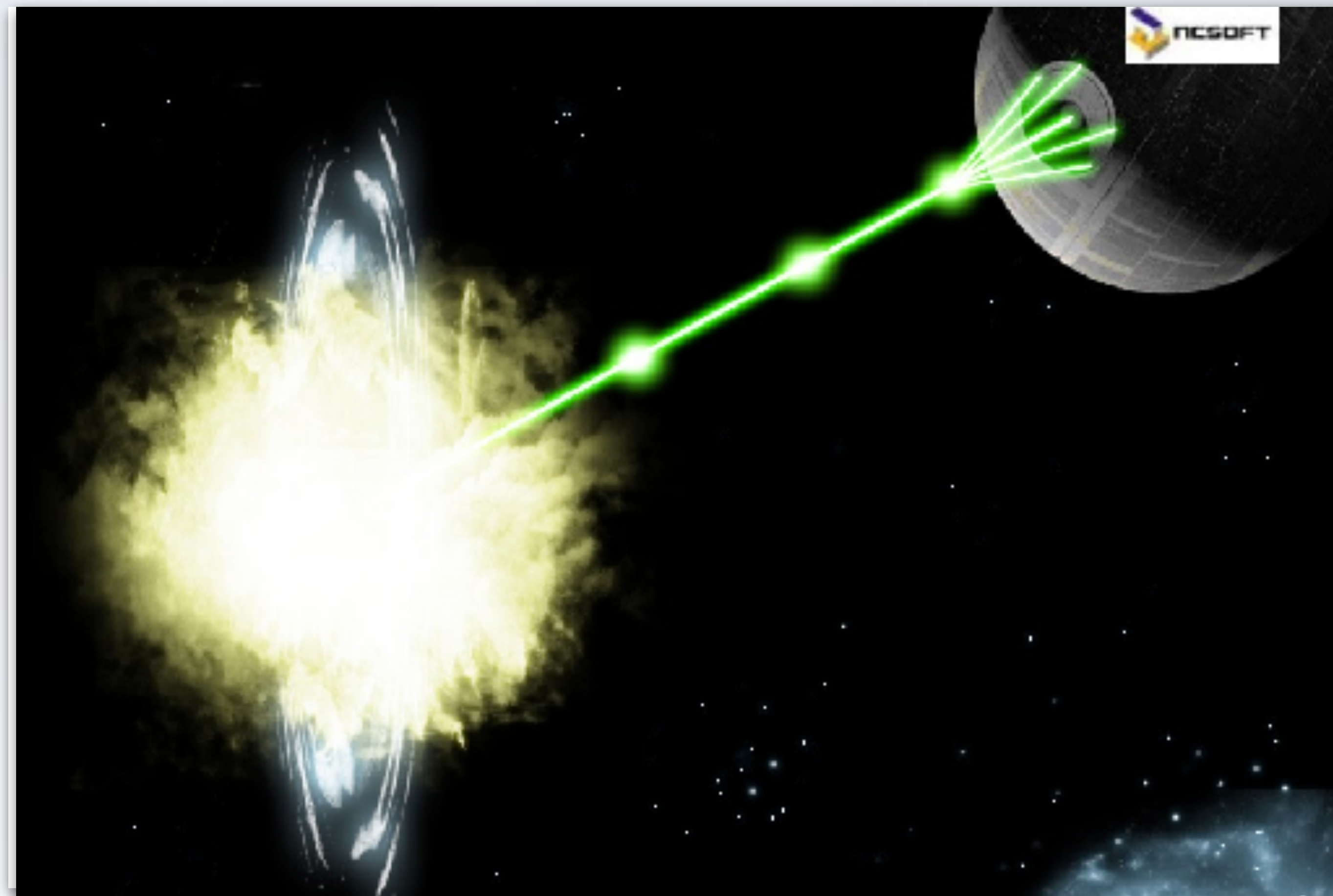

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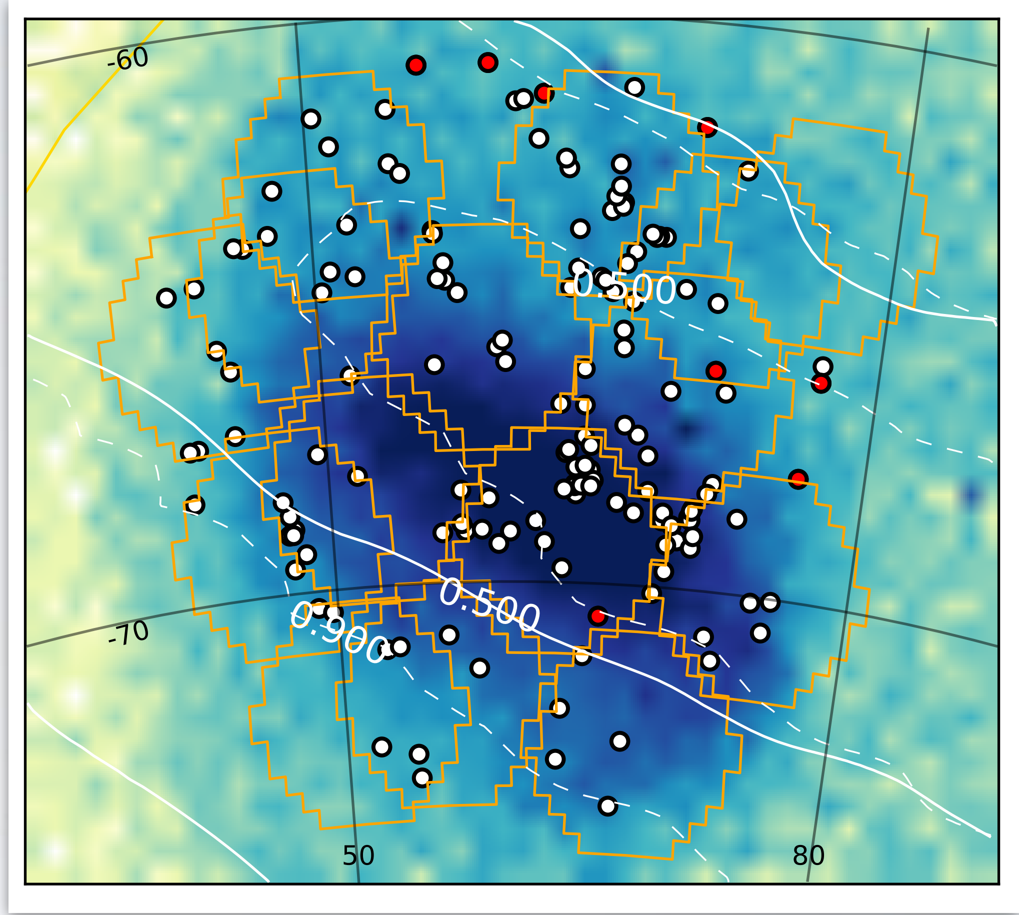
ANALYSIS 2

Search for disappearing stars in the LMC (Annis et al. 2016)

We take possible progenitors (152 red supergiants) catalogued in the literature, and search for them via visual inspection. 144 were in the observed area; all accounted for.

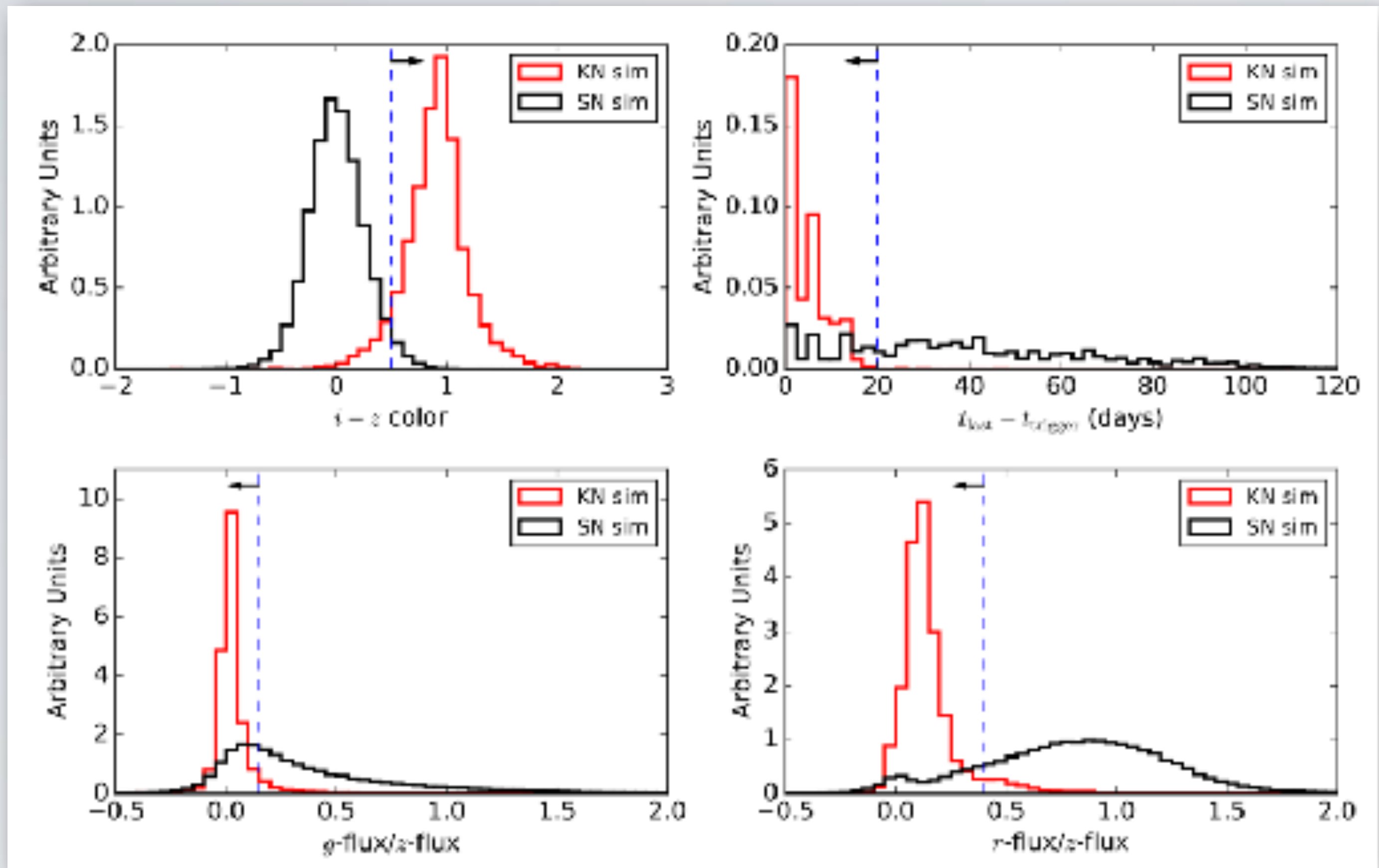
We concluded that the GW event was unlikely to arise from a failed SNe.

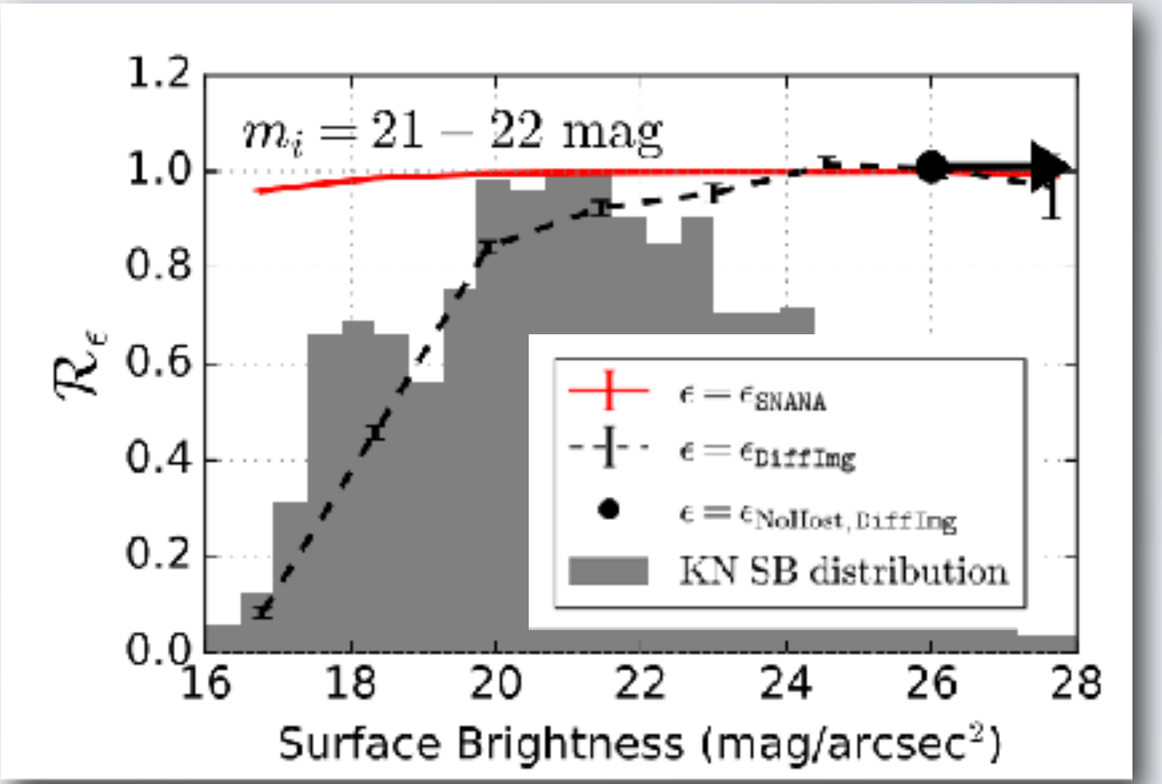


After LIGO's result became public we learned that G150914 was a BBH merger. **This type of search is a template for future GW events, specifically those likely to be a CC event.**

ANALYSIS 4

Search for Kilonovae in DES (Doctor et al. 2017)

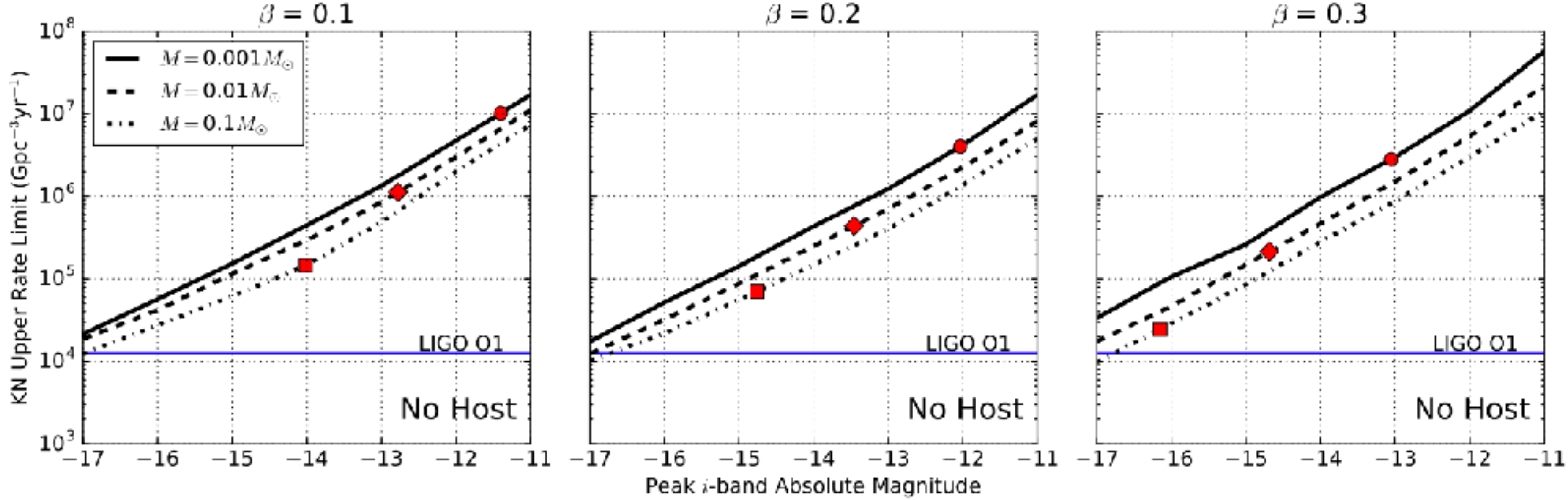




We developed cuts, and studied the efficiency of the search, using simulations.
We learned that difference imaging close to bright galaxies is an issue.

ANALYSIS 4

Search for Kilonovae in DES (Doctor et al. 2017)



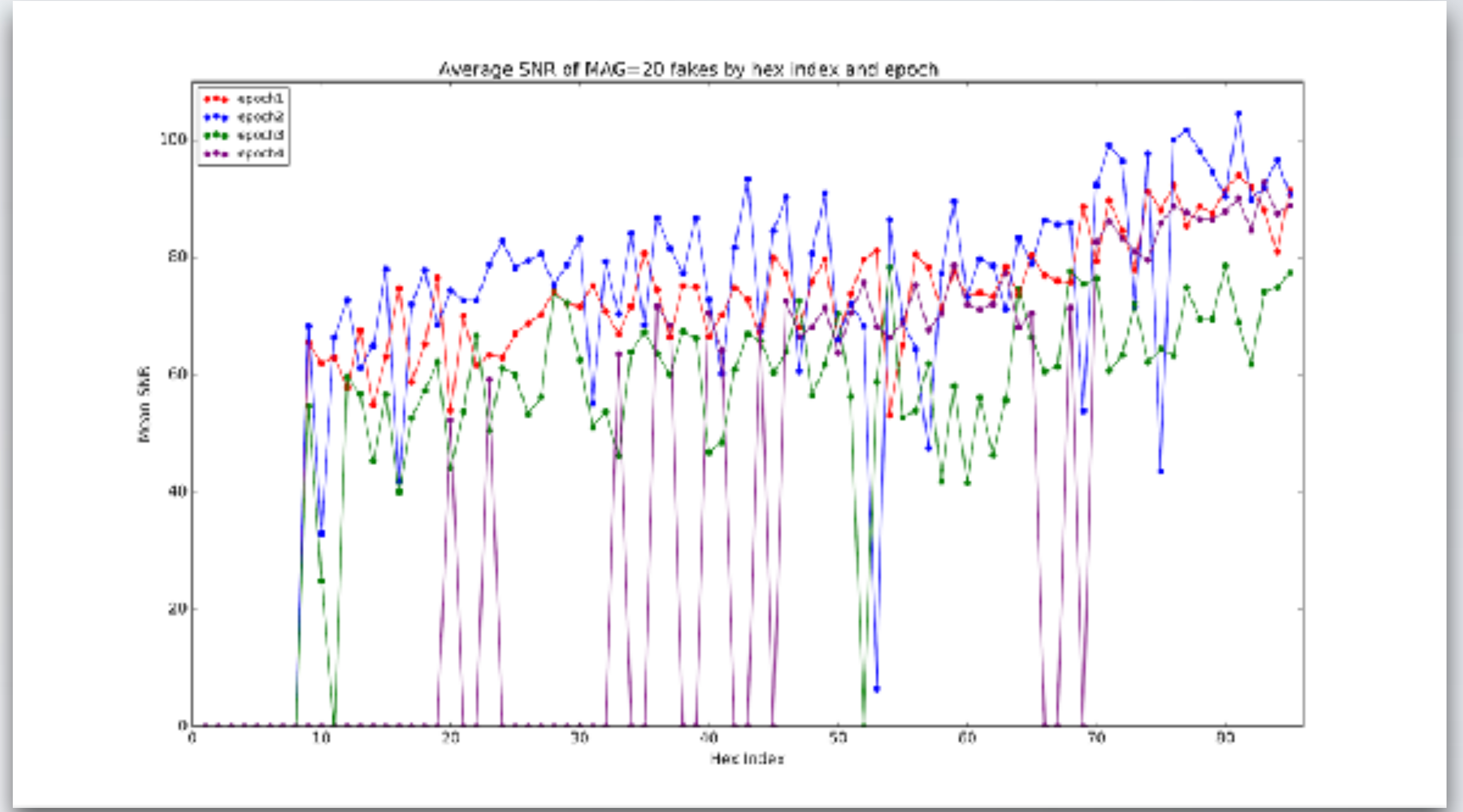
Results for nine values of the parameters (M, \beta) from Barnes & Kasen 2013 (BK13). The points show results fixing the absolute magnitude parameter to BK13's best fit values. The lines show the results varying the absolute magnitude parameter.

IMAGE PROCESSING PIPELINE

Completely automated job submission immediately after search image available.

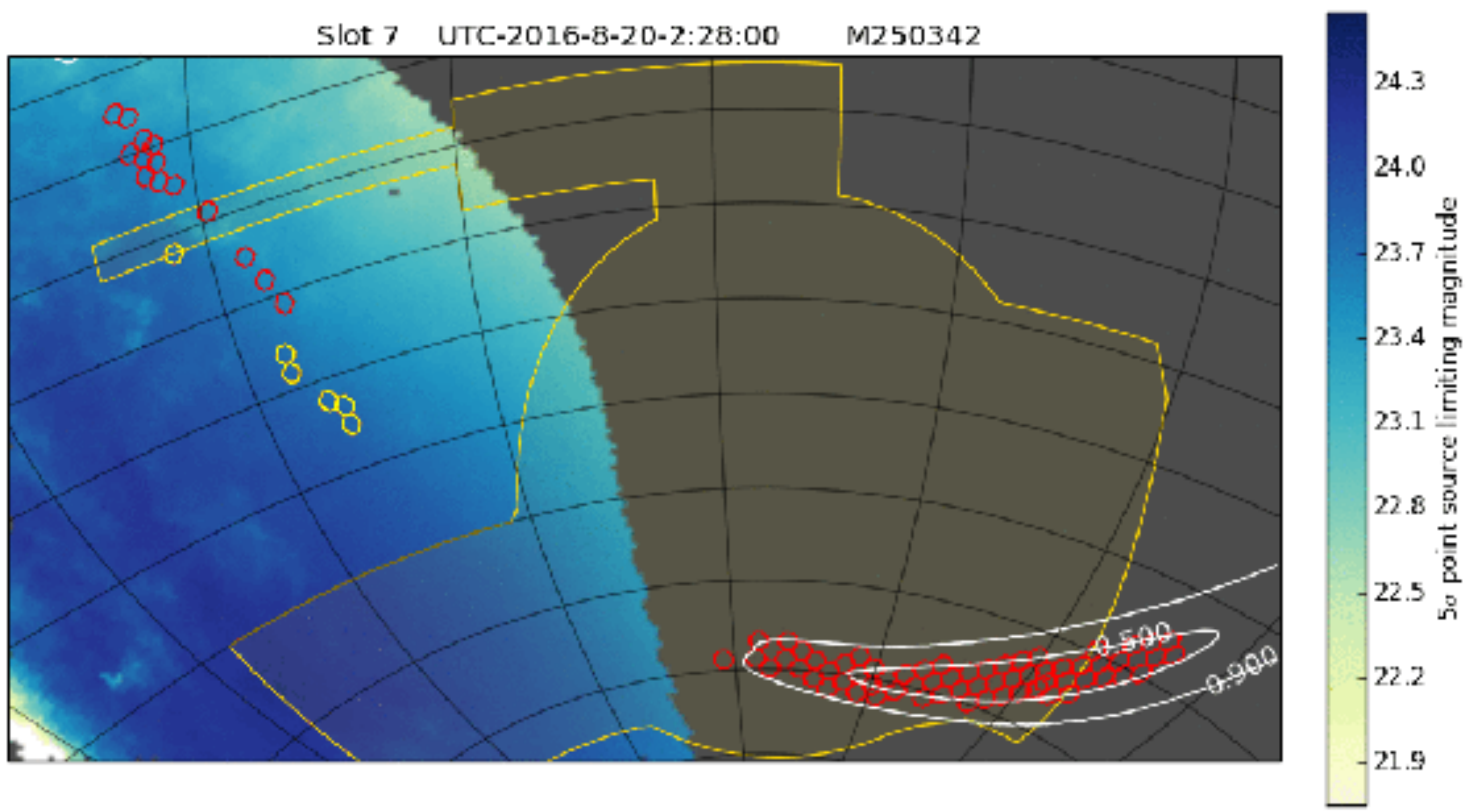
Able to run dozens of images in parallel using Fermilab and Open Science Grid.

Team includes senior scientists, PhD students, and undergraduate interns.

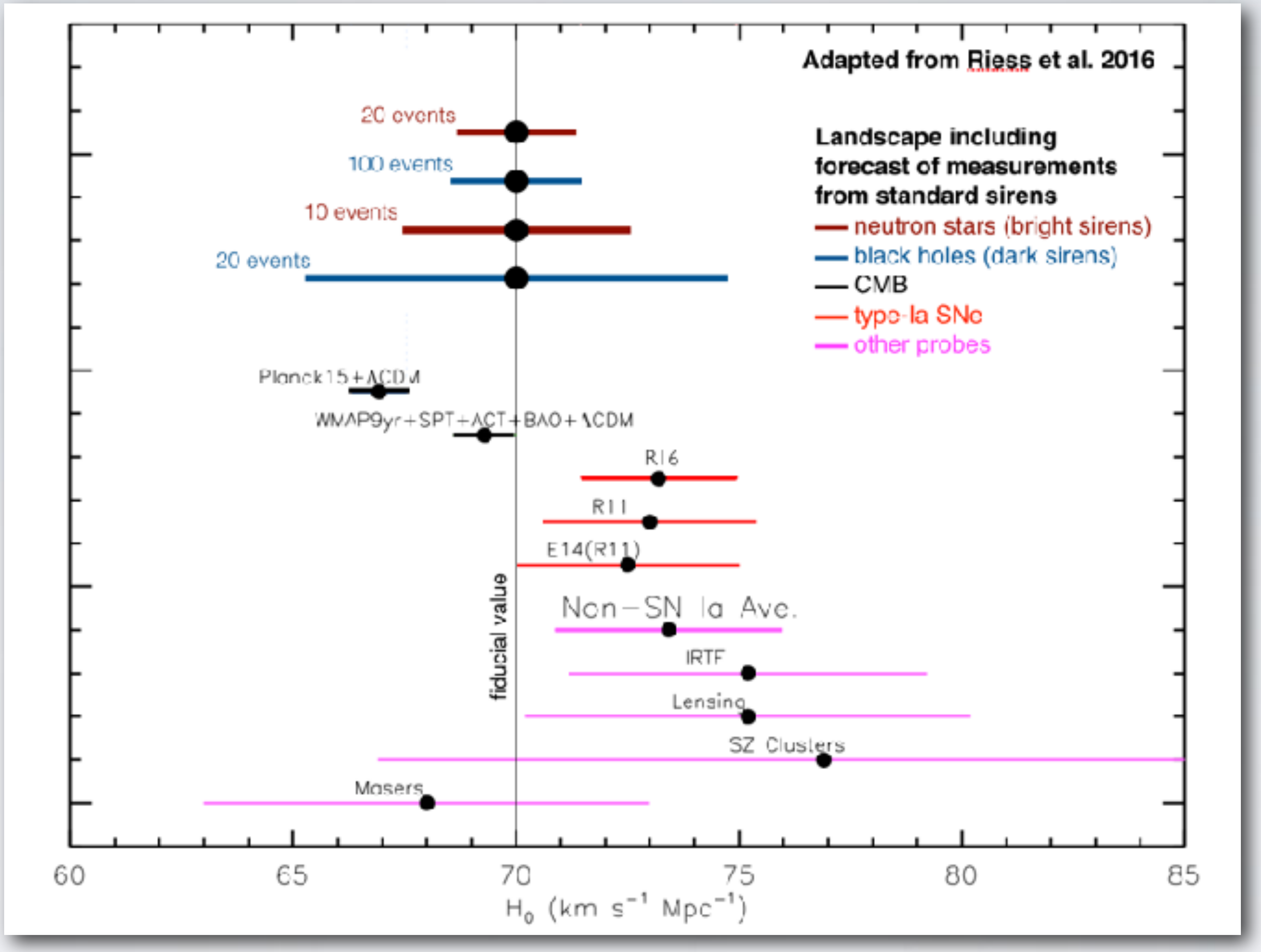


Plot by Bobby Butler, undergraduate student intern.

SIMULATED EVENT



COSMOLOGY PROSPECTS



THE PROGRAM

GW trigger
- time stamp
- sky region
- distance
- event type

~24h

DECam search system
- prepare template images
- schedule observations
- take new images
- perform image subtraction
- detect, model counterpart

LIGO: arXiv:1304.0670

We are here!

O1

	Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within $5\ \mathrm{deg}^2$	$20\ \mathrm{deg}^2$
aLigo	2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
aLigo	2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
aVirgo + aLigo	2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
aVirgo + aLigo	2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
	2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

DES observations (Sep-Feb months)

LSST era!

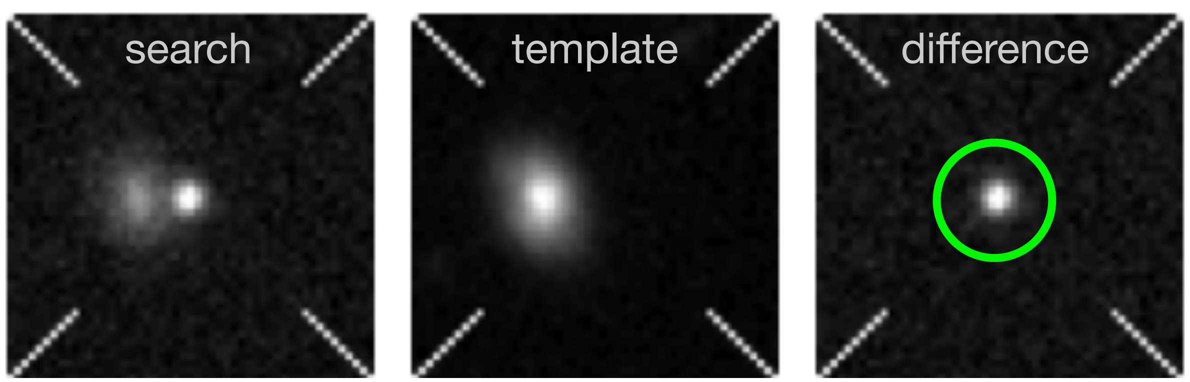
DIFFERENCE IMAGING

Each search image and template run through ***single epoch*** processing (few hours each)

Then each CCD in each search image goes through ***difference imaging*** in parallel (~1hr/job)

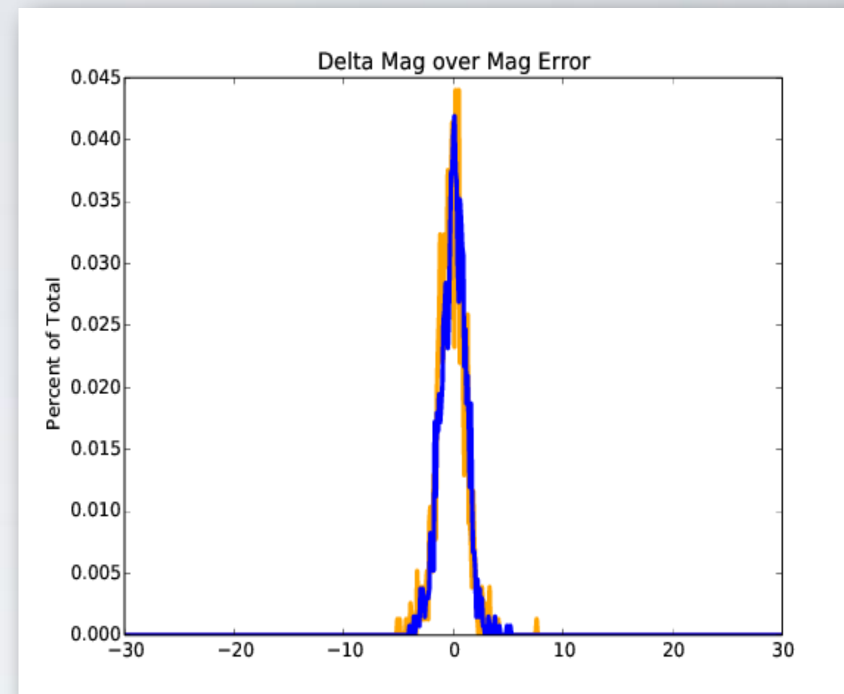
Finally ***post-processing*** does assessment of outputs and creates the candidates list.

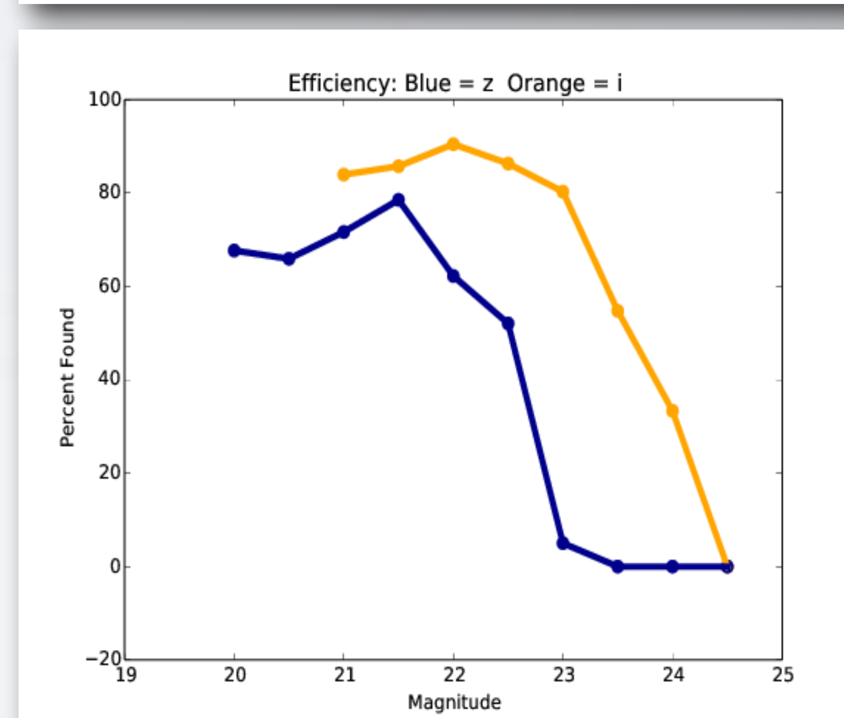
Example of SNe detection using the DES difference imaging pipeline.



The Difference Imaging Pipeline for the Transient Search in the Dark Energy Survey

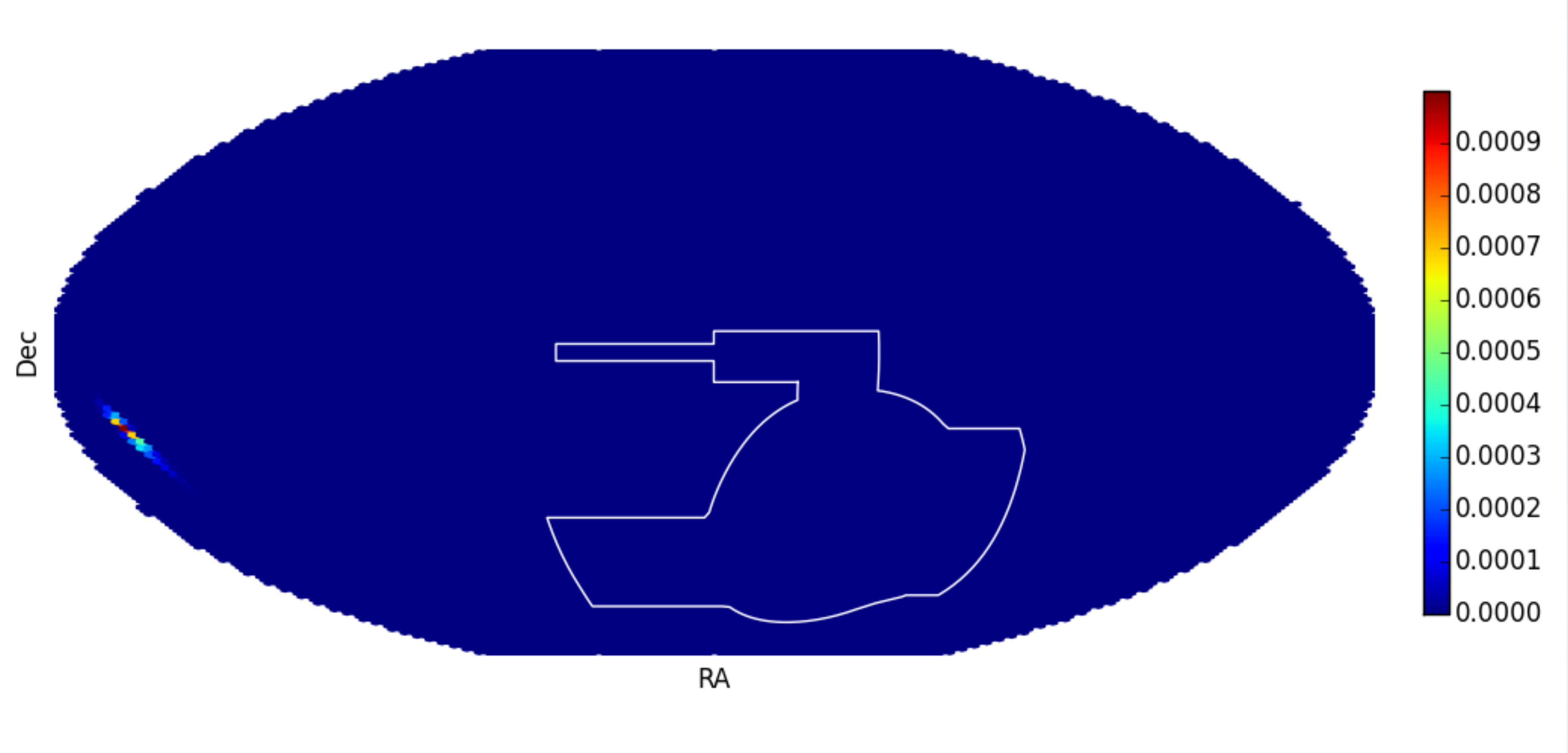
Kessler, et al. 2015, AJ, 150, 172





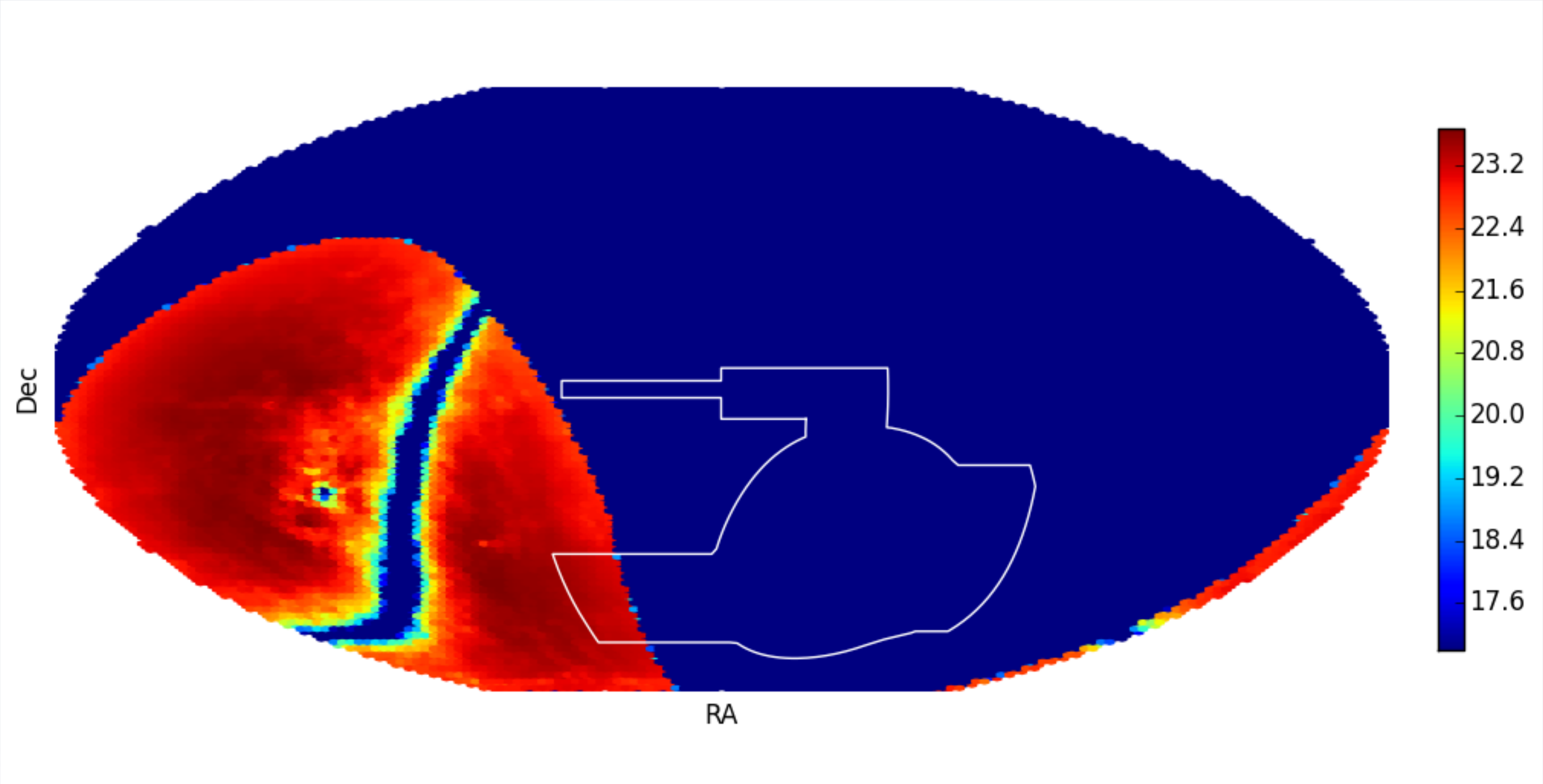
Plots by Tim Osborn, summer intern.

GW170817



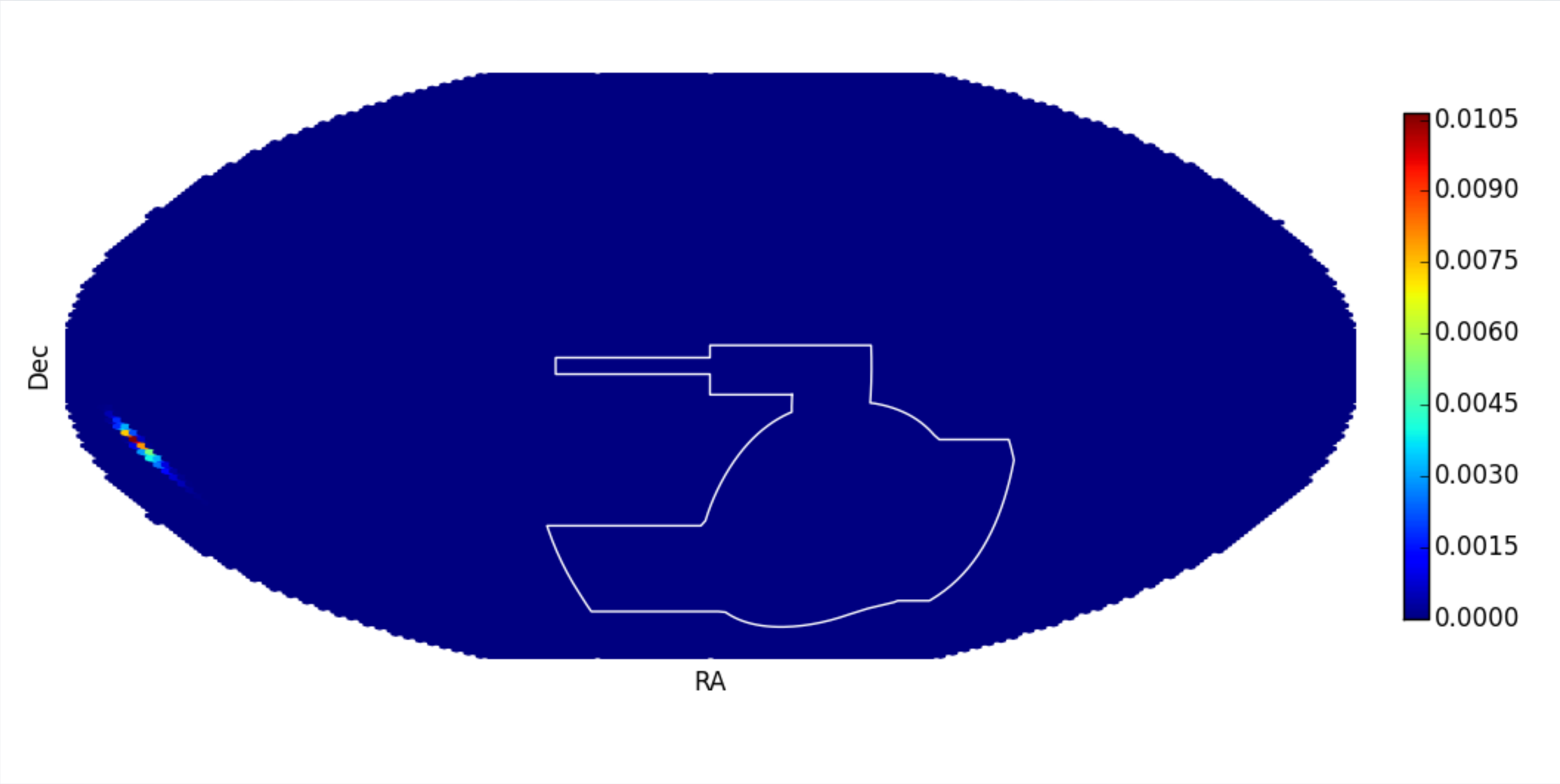
DESGW x LIGO source detection probability map

GW170817



DESGW mag limit model (for 90 sec exposures)

GW170817

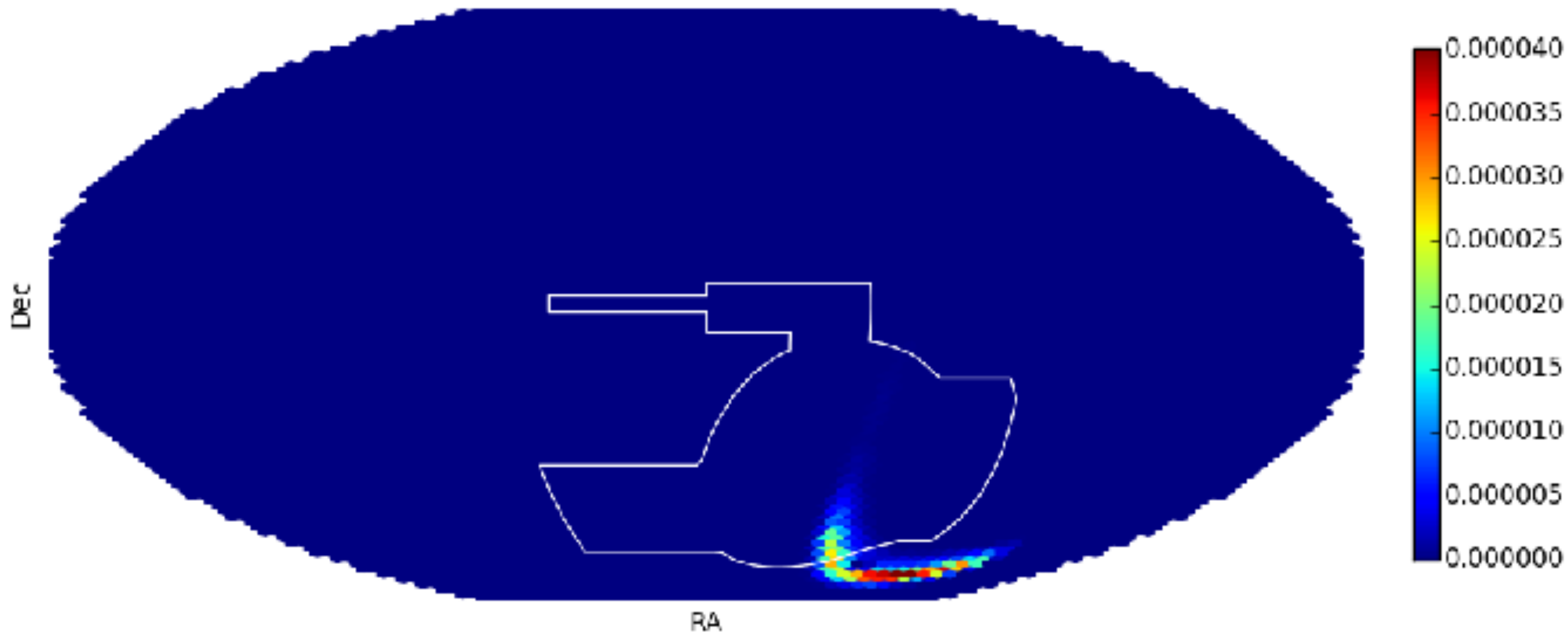


LVC sky localization probability map

GW150914

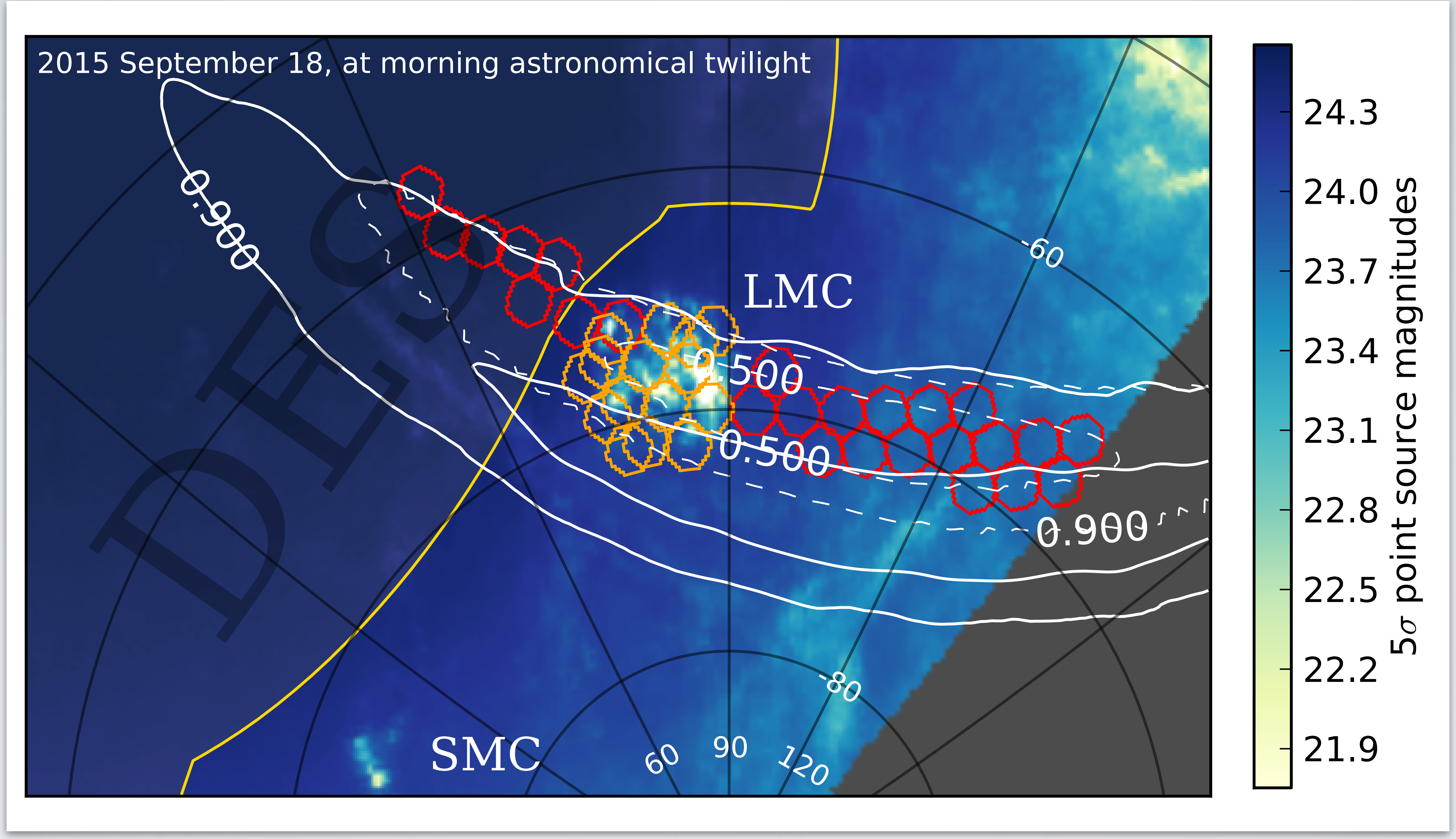
Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

Obs time: 2015 Sep 18
(end of the night)



DESxLIGO source detection probability map

DATA



2015 September 18, at morning astronomical twilight
DES
LMC
SMC
0.900
0.500
0.500
0.900
-60
-80
60
90
120
24.3
24.0
23.7
23.4
23.1
22.8
22.5
22.2
21.9
5σ point source magnitudes